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NORTH ATLANTIC TREATY ORGANISATION

RESEARCH AND TECHNOLOGY ORGANISATION
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RTO AGARDograph 300

Flight Test Techniques Series – Volume 21

Flying Qualities Flight Testing of Digital Flight Control Systems

(les Essais en vol des performances des systèmes de commande de vol numériques)

This AGARDograph has been sponsored by the SCI-055 Task Group, the Flight Test Technology Team of the Systems Concepts and Integration Panel (SCI) of RTO.

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Flying Qualities Flight Testing of Digital Flight Control Systems

(les Essais en vol des performances des systèmes de commande de vol numériques)

by
F. Webster
(Air Force Flight Test Center – Edwards AFB)
and
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(BAE Systems)

This AGARDograph has been sponsored by the SCI-055 Task Group, the Flight Test Technology Team of the Systems Concepts and Integration Panel (SCI) of RTO.

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• SCI	Systems Concepts and Integration Panel
• SET	Sensors and Electronics Technology Panel

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Flying Qualities Flight Testing of Digital Flight Control Systems

(RTO AG-300 Vol. 21 / SCI-034)

Executive Summary

This document covers a wide range of subjects which are applicable to the flying qualities flight testing of Digital Flight Control Systems (DFCS). By necessity, the technical depth and disciplines involved in testing such systems cover a wide range of specialties. The job of flight testing a DFCS is really that of a systems development and integration problem. The DFCS depends on many other aircraft characteristics, systems, and subsystems in order to operate properly and perform its intended mission. Each must perform adequately in order for the entire DFCS to properly operate.

This report covers specific areas deemed especially important by the author, specifically the test preparation and data analyses sections. Proper preparation and data analyses are cornerstones of any successful flight test program, and as such have been given broad attention in this report. In addition, the consequences of potential mistakes while testing a DFCS can be disastrous, leading to loss of aircraft or life. Since this type of flight testing is often hazardous, it is incumbent on the test team to carefully plan and execute the program. The test team must be knowledgeable about what the aircraft is predicted to do, what it is doing, and the reasons for both. Armed with this knowledge, the DFCS flight test team can make the appropriate decisions required during the execution of the test program. Without minimizing the other areas involved, the author believes that preparation and data analyses are the two most important aspects of testing hence the emphasis on these areas.

Lastly, the procedures and practices presented in this report are a compilation of best practices as learned over the years by the test community. They certainly are neither exhaustive nor all-inclusive, but simply a list of perhaps the most commonly used practices. There never has been, nor will there ever likely be, a test program where it is possible or practical to employ all of the practices discussed in this report. However, it is hoped that the reader will find many of the practices applicable to their test programs and be able to improve both test efficiency and safety as a result.

les Essais en vol des performances des systèmes de commande de vol numériques

(RTO AG-300 Vol. 21 / SCI-034)

Synthèse

Ce document couvre un grand éventail de sujets se rapportant aux évaluations en vol des performances des systèmes de commande de vol numériques (DFCS). C'est la conséquence logique du fait que la complexité technique et les disciplines associés aux essais de tels systèmes impliquent un grand éventail de spécialités. La réalisation des essais en vol d'un DFCS n'est rien moins qu'un problème de développement et d'intégration de systèmes. Le DFCS dépend de nombreux autres systèmes, sous-systèmes et caractéristiques aéronautiques pour pouvoir fonctionner et exécuter sa mission. Chacun de ces éléments doit fonctionner correctement afin que l'ensemble du DFCS puisse remplir ses fonctions.

Ce rapport couvre des domaines spécifiques considérés par l'auteur comme particulièrement importants, et en particulier ceux de la préparation des essais et de l'analyse des données. La réussite d'un programme d'essais en vol passe en effet par une préparation et une analyse de données adéquates, ce qui explique la large place accordée à ces sujets dans le rapport. En outre, les conséquences d'éventuelles erreurs lors des essais des DFCS peuvent être catastrophiques, entraînant la perte de vies et de matériel. Puisque ce type d'essais en vol est souvent risqué, il incombe à l'équipe d'essais de préparer et d'exécuter le programme avec le plus grand soin. L'équipe d'essais doit bien appréhender le comportement prévu de l'aéronef, son comportement réel, ainsi que les raisons de ces deux comportements. Forte de ces connaissances, elle sera en mesure de prendre les bonnes décisions lors de l'exécution du programme d'essais. Sans vouloir réduire l'importance des autres éléments concernés, l'auteur est de l'avis que la préparation et l'analyse des données sont les deux aspects les plus importants des essais, ce qui explique l'importance qu'il leur accorde.

Enfin, il est à noter que les procédures et les pratiques présentées dans ce rapport sont la synthèse des meilleures pratiques telles qu'élaborées au fil des années par les spécialistes du domaine. Elles ne sont ni exhaustives, ni complètes mais représentent simplement une liste des pratiques les plus courantes. Pour des raisons pratiques, il n'y a jamais eu, et il n'y aura probablement jamais, de programme d'essais capable d'incorporer l'ensemble des pratiques examinées dans ce rapport. Cependant, il est à espérer que le lecteur pourra appliquer un certain nombre de ces pratiques à ses programmes d'essais et améliorer ainsi leur efficacité et leur sécurité.

Note de traduction : l'auteur insiste lourdement dans le 2ème paragraphe sur la préparation des essais et l'analyse des données. Je n'ai pas modifié le texte mais je suggère de supprimer la 2ème phrase du paragraphe : « La réussite d'un programme d'essais en vol passe en effet par une préparation et une analyse de données adéquates, ce qui explique la large place accordée à ces sujets dans le rapport ».

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Preface

AGARDograph Series 160 and 300

The Systems Concepts and Integration (SCI) Panel has a mission to distribute knowledge concerning advanced systems, concepts, integration, engineering techniques, and technologies across the spectrum of platforms and operating environments to assure cost-effective mission area capabilities. Integrated defence systems, including air, land, sea, and space systems (manned and unmanned) and associated weapon and countermeasure integration are covered. Panel activities focus on NATO and national mid- to long-term system level operational needs. The scope of the Panel covers a multidisciplinary range of theoretical concepts, design, development, and evaluation methods applied to integrated defence systems.

One of the technical teams formed under the SCI Panel is dedicated to Flight Test Technology. Its mission is to disseminate information through publication of monographs on flight test technology derived from best practices which support the development of concepts and systems critical to maintaining NATO’s technological and operational superiority. It also serves as the focal point for flight test subjects and issues within the SCI Panel and ensures continued vitality of the network of flight test experts within NATO.

These tasks were recognized and addressed by the former AGARD organization of NATO in the form of two AGARDograph series. The team continues this important activity by adding to the series described below.

In 1968, as a result of developments in the field of flight test instrumentation, it was decided that monographs should be published to document best practices in the NATO community. The monographs in this series are being published as individually numbered volumes of the AGARDograph 160 Flight Test Instrumentation Series.

In 1981, it was further decided that specialist monographs should be published covering aspects of Volume 1 and 2 of the original Flight Test Manual, including the flight testing of aircraft systems. The monographs in this series (with the exception of AG 237, which was separately numbered) are being published as individually numbered volumes of the AGARDograph 300 Flight Test Techniques Series.

At the end of each AGARDograph 160 Flight Test Instrumentation Series and AGARDograph 300 Flight Test Techniques Series volume is an annex listing all of the monographs published in both series.

OVERVIEW

This document covers the basics of flying qualities flight testing for digital flight control systems. Most of the techniques and subjects discussed also apply to analog systems as well. The techniques discussed are by no means the only techniques available, nor are they necessarily applicable to every flight test program. Rather, they are a collection of best practices from organizations across NATO, which practice the subject matter. The author hopes that the contents of this text will provide a comprehensive overview of the subject appropriate for experienced engineers, as well as provide a learning source for those new to the subject matter.

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1.0 INTRODUCTION

This document covers the basic technical aspects of flight testing the stability, control, and handling qualities of the digital flight control system (DFCS). Significant attention is given to test program preparation. Proper preparation sets the tone and flow of the entire flight test program and often receives insufficient attention. Following the preparation section, the discussion will proceed with the same level of detail to the execution, analysis, evaluation, and reporting of test results. The author will not attempt to teach basic DFCS theory and application. However, in recognition of the fact that the flight test engineer may not have an in-depth background in the subject matter being discussed, simplified examples and references will be liberally used, which will hopefully direct the reader toward obtaining the required skills and knowledge.

Most of the skills necessary to adequately flight test a DFCS covers the breadth of the basic flying qualities theory and flight testing. In this document, flying qualities is used as an all encompassing term to include stability, control, maneuverability, and pilot-in-the-loop handling qualities. Stability and control will refer to the pilot-out-of-the-loop characteristics of the aircraft, as an example, stability margin, control power, time to double or half amplitude, and time to roll 90 degrees. Handling qualities will be those characteristics associated with the pilot in active control of the vehicle, in a sense closing the loop on a second flight control system (FCS).

The DFCS flight test team must be able to competently deal with a broad range of engineering disciplines, ranging from classical stability and control to modern systems theory. They must be able to equally comprehend basic system and subsystem operation, classical, modern, and digital control theory as well as the less scientific discipline of handling qualities. The DFCS flight test team must bring to the problem the theoretical knowledge of the design engineer combined with the practical and operational knowledge of a flight test engineer.

2.0 GENERAL CONSIDERATIONS

2.1 Background

Much has been written in recent years regarding flying qualities problems with the DFCS, in particular, pilot-in-the-loop oscillations (PIOs). The implication has been that there is something inherently deleterious to stability, control, and handling qualities with the use of digital, as opposed to analog, control laws. While the DFCS does offer some unique characteristics, the above assumption is not necessarily warranted. Similar types of handling and flying qualities problems can and do exist with analog control systems. Many of the perceived difficulties with DFCS can be attributed as much to design practices and parallel technical developments as to the process of digitization itself. Most practices and techniques described in this document can be equally applied to analog as well as digital systems flight test.

2.2 Digital Flight Control Systems Considerations

The impact of digital control systems on aircraft flying qualities can be broken into four categories. Two deal directly with digital implementation and the third involves developments in airframe technology. The fourth category deals with the improper application of linear systems theory to an inherently nonlinear mechanism—the airplane.

The first major difference between an analog and digital control system is the process of digitization itself, combined with the operation of a digital computer. The digitization process and discrete nature of a digital computer necessarily leads to time delays. Time delay can be directly related to increased phase lag, which in turn can adversely impact both system stability and handling qualities. Digitization of an analog signal adds time delays since sampled data are held constant over the time between samples. The time between samples and the frame rate is dependent on the computer's internal architecture and the amount of computations to be accomplished. In a digital computer, this process takes a finite amount of time. Another source of time delay is the input/output process of the computer. Each computer takes additional time beyond the actual computation period to deal with the input/output communications to external systems such as actuators or other computers. This additional delay can accumulate or increase if multiple computers in series are used. Most modern computers have sufficient individual throughput capability to minimize the effects of time delay. However, system architecture and the practice of multiple computers in series can, to some extent, negate the throughput times available in modern computers.

Secondly, the flexibility of the DFCS allows for more complex control law implementations than do analog systems. The more complex implementations can include nonlinear dynamics in an attempt to more accurately represent real aircraft flight dynamics compared to the simplified, linearized mechanisms in analog systems. The increased use of nonlinear elements can and does have a large beneficial impact on flying qualities, but can also have deleterious effects. Stabilization and control, more in line with the inherent nonlinear flight dynamics, can be extremely beneficial; however, the lack of a unifying, nonlinear systems theory makes analysis and problem detection difficult in this type of system. This, in turn, can lead to unanticipated flight test problems. The use of extensive nonlinear simulation as an integral part of control system development is common today among most major airframe contractors. This is very effective in minimizing the potential negative impacts of the increased flexibility while maintaining the benefits. Smaller, inexperienced companies often do not have the experience base and may tend to de-emphasize the importance of nonlinear simulation. The DFCS flight test team must keep this in mind when preparing for the test program.

Thirdly, modern technologies emphasizing maneuverability, super-cruise, and low observability often lead to airframe characteristics, which have low stability, combined with low control surface power. This combination usually requires high-gain closed-loop systems, which can significantly amplify the impact of system nonlinearities and structural interactions. Additionally, flying qualities difficulties with high-gain systems range from stability problems to potentially severe handling qualities problems such as PIO.

Fourth, the misapplication of linear design and analysis theory beyond regions of validity, combined with the additional flexibility of the DFCS can cause problems. Aircraft are inherently nonlinear; both in the traditional systems sense (e.g., dead bands, rate limits, and hysterisis), but also with respect to basic flight mechanics. The six degree-of-freedom (6-DOF) equations of motion for a rigid body are highly nonlinear in the kinematics and can have significant aerodynamic nonlinearities. This aspect is often ignored or insufficiently understood and the aircraft dynamics are simply treated as linear transfer functions or set-of-state-space matrices. Application of linearized equations of motion and aerodynamics beyond appropriate assumptions can cause major problems. A thorough understanding of the nonlinear equations of motion and the applicable range of valid linearization assumptions is essential for the DFCS flight test team. This is not to imply that linear theory and analysis is not useful and applicable to the aircraft; however, its application is only as good as the assumptions made. Violation of linearization assumptions will result in invalid design and analysis of the system to be flight tested. This problem is not unique to the DFCS; however, the additional flexibility previously mentioned can exaggerate the problems. Fortunately, the increased use of 6-DOF simulation prior to flight can often catch many of the errors cause by the over simplification of a nonlinear system.

3.0 FLIGHT TEST PREPARATION

3.1 Background

The role of proper preparation for the DFCS flight test program cannot be over emphasized. Adequate preparation begins by obtaining the correct knowledge and skills and using this knowledge to design an efficient and safe test program well before the actual flight portion of the test program. Knowledge will increase as the test program progresses, and this knowledge must be used to continually re-evaluate the program’s progress. In order to provide the correct understanding of the system under test, careful preparation must be accomplished from the initial design stage through flight test reporting and to the final system release for operational use stage. Lack of proper preparation will invariably result in a poorly executed test program and possibly a poor final product to the operational user.

3.2 Understanding the System

Understanding the system under test is key to the adequate development of a ground and flight test plan as well as evaluating the test results. Trying to test a system with a black box mentality of analyzing only the inputs and outputs without understanding the internal workings will result in a poorly designed test program. The breadth of basic knowledge required to adequately flight test a DFCS requires a great deal of background education as well as practical experience. This section will point out the key areas of specific system knowledge required to adequately plan, conduct, and evaluate ground and flight testing of a DFCS.

There are eight areas of the overall aircraft system with which the DFCS flight test team must become familiar. These are mass properties, aerodynamics, control laws, actuation systems, structural dynamics, sensors, redundancy management, and subsystems. The following paragraphs will describe the key items of knowledge required in each of these areas.

3.2.1 Mass Properties

The mass properties of interest are the gross weight, three axis centers-of-gravity (cg) locations, and the moments and products of inertia. The engineer should be familiar with the potential range of each of these variables with different fuel and store loadings to be evaluated. Mass properties directly impacts performance of any system, as they are physically a part (along with aerodynamics) of determining the unaugmented or bare airframe characteristics. Prior to having actual hardware, the mass properties are usually estimated by the contractor’s weights group. The estimated mass properties often change over the course of the design process as the final system matures. The estimations range from broad empirical estimates in conceptual design, to very careful bookkeeping of individual component properties and locations as the design matures. Modern computer-aided design (CAD) systems have proven to be very accurate in providing the estimated mass properties for aircraft. When such systems are used, they can greatly enhance the capability to predict the mass properties prior to having actual hardware. However, even when CAD systems are used, the final weight and cg characteristics should be directly measured on scales during a weight and balance session. Inertias continue to be estimated with an analytical component build-up procedure. Alternative methods have been developed and successfully used on light or small aircraft to measure the inertias, but these methods have not met with success when applied to heavier and larger aircraft. For most applications relative to military aircraft, the inertias are computed with a detailed component build-up procedure.

3.2.2 Aerodynamics

The DFCS flight test team should be familiar with the general aerodynamic characteristics of the aircraft across the flight envelope. This includes not only the traditional linear stability and control derivatives, but also the nonlinear characteristics. Traditional stability and control derivatives are particularly useful within the heart of the normal operating envelope; however, at the envelope extremes (e.g., high angle-of-attack [AOA] and large sideslips) their usefulness may diminish as significant nonlinearities occur. These nonlinearities will directly impact the stability and controllability of the aircraft and must be understood in order to design a test program which will adequately evaluate the DFCS.

Within the heart of the flight envelope, the aircraft aerodynamics are often linear and may be well defined by the primary stability and control derivatives. The DFCS flight test team should be familiar with these derivatives and their variation with Mach number, AOA, dynamic pressure, and sideslip. Below are some of the traditional stability and control derivatives the DFCS flight test engineer should become familiar with for the airframe of interest.

$$
\begin{array}{lllll}
Cm_{\alpha} = \dfrac{\partial Cm}{\partial \alpha} & Cl_{\beta} = \dfrac{\partial Cl}{\partial \beta} & Cn_{\beta} = \dfrac{\partial Cn}{\partial \beta} & Cy_{\beta} = \dfrac{\partial Cy}{\partial \beta} & CL_{\alpha} = \dfrac{\partial CL}{\partial \alpha} \\
Cm_{q} = \dfrac{\partial Cm}{\partial \hat{q}} & Cl_{p} = \dfrac{\partial Cl}{\partial \hat{p}} & Cn_{p} = \dfrac{\partial Cn}{\partial \hat{p}} & Cy_{p} = \dfrac{\partial Cy}{\partial \hat{p}} & CL_{q} = \dfrac{\partial CL}{\partial \hat{q}} \\
Cm_{\delta} = \dfrac{\partial Cm}{\partial \delta} & Cl_{r} = \dfrac{\partial Cl}{\partial \hat{r}} & Cn_{r} = \dfrac{\partial Cn}{\partial \hat{r}} & Cy_{r} = \dfrac{\partial Cy}{\partial \hat{r}} & CL_{\delta} = \dfrac{\partial CL}{\partial \delta} \\
Cm_{\beta} = \dfrac{\partial Cm}{\partial \beta} & Cl_{\delta} = \dfrac{\partial Cl}{\partial \delta} & Cn_{\delta} = \dfrac{\partial Cn}{\partial \delta} & Cy_{\delta} = \dfrac{\partial Cy}{\partial \delta} &
\end{array}
\tag{1}
$$

where:

CL,Cy = lift and side force coefficients,
Cl,Cm,Cn = Nondimensional roll, pitch, and yaw coefficients,
α = Angle of attack,
β = Angle of sideslip,
δ = Control surface deflection,
p,q,r = Roll, pitch and yaw rates,
$\hat{p}, \hat{q}, \hat{r}$ = Nondimensionalized body axis rates, $\frac{pb}{2V_t}, \frac{q\bar{c}}{2V_t}, \frac{rb}{2V_t}$,
$\bar{c}$ = Mean aerodynamic chord,
b = Wing span,
V_t = True airspeed, and
∂ = Partial derivative operator.

The primary static stability derivatives (CL$_{\alpha}$,Cm$_{\alpha}$, Cn$_{\beta}$, and Cl$_{\beta}$) determine the bare airframe static stability. The damping derivatives (Cm$_{q}$, Cn$_{r}$, Cl$_{r}$, Cn$_{p}$, and Cl$_{p}$) will determine the damping characteristics, and when combined with the static stability derivatives, mass properties and flight condition will determine the overall bare airframe stability. The control derivatives (Cm$_{\delta}$, Cn$_{\delta}$, and Cl$_{\delta}$), combined with the stability and damping derivatives, will determine the control law architecture and gains required to achieve the desired flying qualities. Control powers are extremely important, and often overlooked. A flight control system's ability to provide the desired flying qualities will depend on its ability to apply the appropriate amount of control necessary to make the bare airframe act as desired. Control power (combined with actuation system dynamics) is the hammer of the flight control system. The most intricate and artfully designed DFCS is only as good as the ability of the overall system to supply sufficient control power in a timely fashion. Low control powers are becoming more common as low observability continues to dictate airframe design.

While the linear stability and control derivatives supply the DFCS engineer with vital information, they are only a part of the story. Aircraft aerodynamics are often nonlinear. This is most often the case at the extremes of the envelope, at or above stall AOA, high sideslip. Nontraditional airframe shapes to accommodate low-observability, post-stall maneuvering, can result in these nonlinearites being closer to the heart rather than the edges of the envelope. The DFCS flight test team must be familiar with the nonlinear characteristics of the total forces and moments (usually in coefficient form) across the envelope. The total coefficients are usually available from a simulation or wind tunnel aerodynamic model. It is vital that the DFCS flight test team obtains these data and become familiar with them. The key force components are lift, drag (or alternatively normal and axial force), and side force coefficients (CL, Cd and Cy, respectively). The key moment coefficients are pitch, roll, and yaw (Cm, Cl, and Cn, respectively). The best way to become familiar with the nonlinear characteristics is to plot the total coefficients as a function of Mach number, AOA, dynamic pressure, and sideslip. The simulation or wind tunnel aerodynamic models can also be used to generate the linear stability and control derivatives.

3.2.3 Control Laws and Actuation Systems

The control strategy, or control laws, will be determined by the desired flying qualities, bare airframe characteristics, available sensor information, control powers, and actuation capability. Actuation systems are an integral part of the control system since they provide the means to provide the necessary control deflections as commanded by the control laws. An actuation system, which cannot keep up with the commands from the control laws, can significantly degrade the flying qualities. The DFCS flight test team should be familiar with the detailed structure of the control laws, including key feedback parameters, command type, gain structure, and filters employed. In addition, information on the actuator dynamics and deflection and rate limits will be required.

There is no single solution to the design of control laws to handle a given set of flying qualities requirements. The effect of various feedbacks employed using classical techniques are well understood and documented in numerous texts on FCS design. This knowledge is a result of many years of classical design experience, combined with a well-defined linear systems theory. The basis of the classical methodology relies on single or simple multiple-loop feedbacks, from which the impact of individual feedbacks and gains are manipulated until acceptable results are achieved. A direct result of the methodology is system architecture from which the impact of a given feedback loop is readily apparent. As an example, a roll-rate feedback to the aileron is a good indication that the roll mode required augmentation. The impacts of roll-rate feedback to the aileron on this mode are well understood from the classical design theory. Newer or so-called modern design methods can change this character of the classically designed system. Requirements for full-state feedback can result in architectures with gains from all states (measured or estimated) to all surfaces. This type of architecture can be difficult to understand by the simple inspection of the block diagram. It is not readily apparent why any given feedback signal and gain is used. In addition to this, use of full-state feedback parameters such as bank angle are usually based on linearized, small angle approximations which may not be valid throughout the maneuvering envelope. Modern techniques have found the most favor in aircraft FCS designs in the areas where limited envelopes of operation apply, such as in autopilots. Inner loop, primary control laws still tend to be designed by classical techniques, but this may well change, as the more modern methods become better understood by designers.

The first place to begin the familiarization process is to obtain a complete and detailed description of the flight control system from the designers. This description should be of sufficient detail such that models can be built for the DFCS flight test team to perform both simplified and detailed analyses of the system. All feedbacks and associated paths, filters, sensor dynamics, nonlinear elements, and actuator dynamics should be included. With this information in hand, combined with knowledge on the aerodynamics and mass properties, the DFCS test team can begin the process of understanding the system.

The DFCS flight test team should thoroughly familiarize themselves with the detailed control laws for the aircraft. This is best accomplished by both studying the detailed FCS description and discussing the design of the system with the designers. In addition to studying the detailed description, the DFCS flight test team should also ask for access to all FCS-related analyses, to include linear, nonlinear and simulation results. The test team should ask the designers for clarification or explanation of analysis results or design decisions. Understanding why a system was designed in the fashion it was leads to a detailed understanding of the system itself. In no way should the DFCS flight test team simply view the DFCS as a black box understandable only by the designers. The team must become thoroughly familiar with the design and expected operation of the DFCS.

3.2.4 Sensors

Sensors are the heart of any DFCS. The sensors provide the control laws with the information required to command the appropriate surface deflections. The DFCS flight test team must familiarize themselves with the required sensor suite for the control laws to operate. All sensor sources are prone to error; the criticality of these errors depends on the system characteristics. The subject of sensor dynamics and design and placement is complex, but the most critical part for the DFCS flight test team are the error sources.

Many design engineers who are not completely familiar with the potential sources of error in the sensor system sometimes design assuming a higher fidelity sensor signal than actually exists. It is often up to the flight test team to point out and be aware of potential error sources and their impact on test efficiency and safety. This section will therefore focus on the potential error sources that can impact the test program.

The following are potential critical data sources for many control laws:

a. Air data, airspeed, altitude, and dynamic pressure,

b. AOA and sideslip,

c. Body axis angular rates (p, q, and r),

d. Body axis accelerations; (N_x, N_y, and N_z), and

c. Euler Angles (ψ, θ, ϕ).

Air data are vital to most control laws in modern aircraft. Many DFCS gains are in some form inversely proportional to dynamic pressure or proportional to the ratio of dynamic pressure to local static pressure. They may be implemented as such, or with functions of Mach number and pressure altitude. Autopilots will often use airspeed or altitude as a parameter to be held constant; they then become feedbacks as well as gain scheduling parameters. The criticality of proper measurement of airspeed, altitude and/or their associated pressures will depend on the design of the system and the bare airframe dynamics. For aircraft in which the control laws are attempting to provide stability to the bare airframe, the criticality is much higher than for a system that is providing limited augmentation of modal damping (i.e., a yaw damper). All air-data measurement systems are subject to errors. The type and severity of these errors depends on the type of system and its placement. Most air data are derived from Pitot-static type systems. These systems will have pressure errors at the static port, and may have total or Pitot errors. The magnitude of the errors will depend on the placement of the system as well as the intended flight envelope. Position error corrections are often predicted, but will only be finally determined via flight test. If the system is sensitive to these errors (as indicated by analyses), then great care must be exercised in planning and executing the envelope expansion program. Position errors are usually largest at transonic speeds; therefore, initial envelope expansion flights at less than transonic speeds may have sufficient Pitot-static error margin. One source of error often ignored is Pitot stall. At high AOA or sideslip, the Pitot tube cannot turn the flow, and subsequently stall the same as with a wing. Again, the criticality of this depends on the overall system, but should not be ignored when proceeding to high AOA testing or testing in regions where departure is a possibility.

Angle-of-attack is another parameter used for gain scheduling and is quite often a feedback parameter. Measurement of AOA is also prone to numerous errors, the criticality of which depends on the system and intended flight envelope. Angle-of-attack is most often measured with fuselage mounted vanes, but other sources are also used. Recent innovations include the use of a series of pressure ports arranged around the nose of the aircraft, commonly called a flush air data system (FADS). The FADS can also be used to measure the airspeed, altitude, and sideslip. Both types of systems are prone to local flow errors. Vanes are usually calibrated during flight test, although initial calibrations are often analytically predicted. Pressure port systems usually require preflight calibration in a wind tunnel as well as calibration from flight test data. Measurement of AOA is subject to induced local velocities from body axis angular rates. A rigid body rotating about the cg will induce velocities off the cg, which will appear as an indicated angle when local flows are measured. These induced velocities are approximately proportional to the body axis angular rate multiplied by the distance from the cg and inversely proportional to true airspeed. For a large transport type aircraft, where small body axis rates are encountered, this may be a small problem. However, for fighter aircraft with large rates, particularly at low airspeeds, body axis rotational rates can induce large errors.

Sideslip is a parameter rarely used to date as a feedback parameter because of the difficulties in obtaining accurate measurements. This may drastically change on future aircraft as bare airframe directional stability is sacrificed to obtain low observability. Sideslip is measured in much the same way as AOA, with either vane or pressure ports. Measurement of sideslip is prone to the same errors as AOA, but is often much more sensitive to local and induced flows. While local flow effects may be on the order of 10 to 20 percent for an AOA vane, they may be as high as 50 percent for a sideslip vane. In addition, convenient location of multiple sources is not as easy as for an AOA vane. In spite of these difficulties, a source of sidelsip measurement is in most cases required to stabilize a bare airframe directional instability; therefore, their use may well increase in the future.

Body axis angular rates are probably the most common and one of the oldest sensor sources used. Accurate measurement is possible with high fidelity rate gyros. Sensor location can be a problem if significant structural modes are present. For most fighter aircraft, the airframe is usually sufficiently rigid to have the structural frequencies well above the primary DFCS frequencies. This allows the use of notch filters to help eliminate structural interaction. The same is not necessarily true for large transport aircraft. For these aircraft, the structural frequencies are often in a range of control required by the FCS, thus eliminating the ability to use notch filters. In addition, these aircraft can have widely varying structural modes, with varying nodes and antinodes as fuel is burned. The potential advent of low-weight and low-observable structures combined with active structural control will even further increase the importance of angular rate sensor placement.

Body axis translation accelerations are also common and long used sensors. These sensors are prone to measurement error dependent on location. Error sources are induced accelerations due to rigid body motion and structural dynamics. The same problems relative to notch filtering for the accelerometers exist as for the body axis angular rates. Body axis measured translation accelerations suffer from incorrect measurements when not located at the cg. Fortunately, the error associated with off cg rigid body measurements can be applied to the benefit of the control laws. Most aircraft place the accelerometers well ahead of the cg, which provides some lead to the signal, and can enhance the ability of acceleration measurements to provide augmentation. However, the converse of placing the accelerometers aft of the cg can have a significant destabilizing impact.

Euler angles or body axis attitudes with respect to the local horizontal are perhaps the oldest forms of sensor signals used in flight control systems. Attitudes are easily measured with mechanical attitude gyros, or as is the common practice today, with strap down rate gyros integrated to obtain attitudes. Their use is generally limited to outer loop autopilots, but in proper form can also be used in inner loop augmentation. The use of bare Euler angles (their use in a nontrigonometric form) is only applicable in flight regimes where small angle approximations are valid. The bare form may be fine for large transport aircraft, which are not highly maneuverable, but can quickly create problems for fighter or trainer aircraft where their use as bare angles violates small angle approximations. When used in an inner loop or even in an autopilot in their bare form, they should always be in conjunction with code to disengage when large bank angles or pitch attitudes are encountered. The problems with bare Euler angles arise from linear analysis theory. The Euler angles only appear in the 6-DOF equations of motion in trigonometric form (e.g., cos, sin). Their bare use arises from small angle approximations used in linear theory where the sin is approximately equal to the angle and the cosine is equal to unity. Consequently, the use of the bare angles rapidly looses validity when small angle approximations are used.

3.2.5 Redundancy Management

Redundancy management (RM) or failure detection and management is a critical element of any DFCS. Critical sensors, computers or communications paths are all considered in RM schemes. Since any system is subject to failure, detection and handling of these failures is critical to the operation of a DFCS. This is particularly true of systems under development. New and unproven systems under development are far more likely to encounter failures than mature systems. For this reason, the DFCS flight test team must be familiar with the RM scheme employed by their particular system, its intended operation and potential weaknesses. Redundancy management is another complex subject with as many schemes as there are flight control systems. However, in spite of this, most have some common basic operating principles.

The RM system is usually designed to provide either fail operational or fail safe operating states. Fail operational means that any failure, or set of failures, will be detected and isolated so that the basic mission is not compromised. Fail safe means that any failure, or set of failures, will result in a vehicle safe to operate and return to base, but the mission may be compromised. Most design specifications for operational aircraft define a set number of critical failures to be fail operational and specified subsequent failures to be fail safe. The general premise is that no single failure should cause loss of mission, and multiple failures must be encountered to significantly reduce the safety of flying. The methods used to achieve this capability usually involve multiple or redundant systems with sophisticated software to detect and isolate failures. The process of isolation often implies a process of elimination. As an example, if three signals are available, and one is substantially different from the other two, than chances are the odd signal is bad and can be ignored. Conversely, if only two signals are available, detection of the bad signal is almost impossible without some third comparison source. The probability of selecting the correct value increases as the number of redundant signals or processes increases. Most modern DFCS systems are either triplex or quadroplex; triplex referring to three separate systems and quadroplex to four. The redundancy level often includes critical sensors, computers and communication paths, but may not include sub-critical paths.

Analysis to determine the critical paths, probability of occurrence and the outcome of an occurrence is accomplished via failure modes and effects analysis (FMEA). This analysis ranges from examination of the block diagrams all the way to evaluating failures via 6-DOF simulations. The results of these analyses will identify the critical paths and the consequences of failures occurring. Large contractors usually employ experts in FMEA and failure modes and effects testing (FMET), which will provide a thorough analysis of the system under consideration. Smaller contractors or projects may not have sufficient resources at hand, and the job may well fall to the DFCS flight test team to determine critical-failure paths and effects. Failure mode analysis usually starts at the component level, then progresses into the subsystem and finally to the entire system. The desire is to achieve a probability of occurrence of a top-end state. The top-end state can range from failure to achieve the mission to loss of the aircraft. A technique called fault-tree analysis is used to provide detailed analysis of potential failure states and their consequences. The fault tree is a diagram progressing from the simplest component (i.e., a rate gyro) or components and proceeds to the top-end event. There may be several layers or levels of events, each of which is combined to provide the probability of loss of mission or aircraft. Figure 1 shows a simplified example of such an analysis.

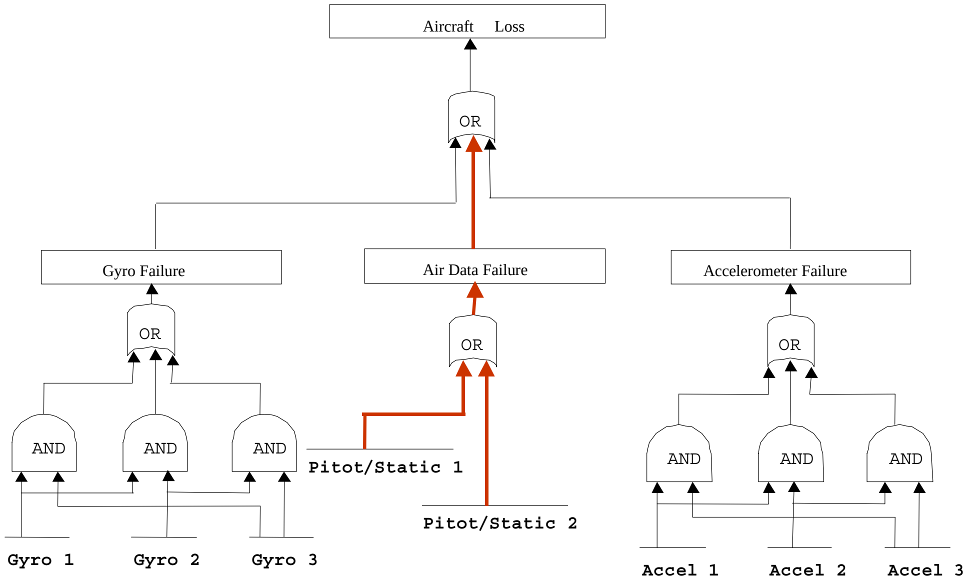

Figure 1 Simplified Fault Tree

The use of *AND/OR* gates are elemental to this analysis. Component level probabilities of failure such as the gyros in Figure 1 are determined by component bench testing and includes operational data if available. The AND gates signify multiple failures required to achieve the failure level (gyro or accelerometer failure Figure 1). For *AND* gates, the probabilities are multiplied together, reducing the probability of occurrence since the probabilities are all less than unity. The *OR* gates are indicators of potential single point failures, either event A *OR* event B can result in the top end event occurring. The probabilities of each are added through these gates, increasing the chance of occurrence. The loss of a single airspeed data source of Figure 1 is an example of *OR* gate operation. A series of *OR* gates unbroken by an *AND* gate is an indication of a potential single point failure. The presence of a series of *OR* gates in such an analysis should always be investigated. The DFCS flight test team needs to be familiar with the FMEA analysis and the potential failure states, which can degrade system operation or safety.

A few words concerning the magnitude of the final numbers of an FMEA are in order. Many times the results of such an analysis will indicate that the chances of a particular failure are 10^{-8} per flight hour, or that it would take 10^{8} flight hours to occur. This implies that an aircraft, which may have a 20,000 or even a 200,000-hour service life, will never see this occurrence. These numbers imply that the event will only occur roughly once in every 10^{5} years. The numbers must not be taken literally, but respectively, i.e., a 10^{-8} occurrence is 100 times less likely than a 10^{-6} occurrence. They must also be taken in relation to some event. As an example if the probability of loss of aircraft is 10^{-8} per flight hour due to a complete failure of the gyros, it means just that. It does not mean that you can fly many aircraft for 10^{8} hours without a crash. The goal is to reduce the numbers to very small values to ensure the safety of the system. At some point, (while the math may give a small probability value), the numbers lose all absolute meaning and become valid only for relative comparisons.

The failure modes effect testing (FMET) is testing for the impact of failures by failing critical paths (indicated by the FMEA) via simulation. In many cases, the criticality of any given failure must be determined by testing, and these results fed back into the FMEA analysis. Testing or other analysis must often be conducted to verify the top end events of the FMEA. Conversely, the initial consensus may be that the aircraft will not lose control with the loss of all three gyros, but simulation testing indicates that this will occur, with a low chance of recovery and a potential loss of the aircraft. Failure modes effect testing is most often accomplished in a simulation with or without actual hardware-in-the-loop. All critical paths should be explored to verify the FMEA and, if necessary, the FMEA should be updated to reflect these results.

An often-neglected path in the FMEA is software failures. The FMEA does not always apply to the software itself, but assumes that the ability to detect and isolate the failures exists. The simplified example of Figure 1 does nothing to indicate the probability of the failures going undetected. For this reason, undetected failures are often analyzed during the FMET phase. This area is important and should not be neglected. The reason for nondetection of failures can be numerous, and are often the result of the actual failure scheme and software employed.

3.2.6 Subsystems

Subsystems such as hydraulics, power supplies, and environmental controls are vital to the operation of any DFCS. For this reason, the DFCS flight test team should familiarize themselves with the primary and backup systems for each. The hydraulic and electrical power supply systems will determine if the DFCS can manipulate the control surfaces through sufficient range and at a sufficient rate to provide the desired flying qualities. Backup systems are quite often not as capable as the primary system, and can lead to problems.

The hydraulic requirements are usually given in terms of the pressure and flow-rate (gallons/minute) capability of both the primary and backup systems. Without sufficient pressure or flow rate, the surfaces cannot move across the required range nor can they get to a given position quickly enough to provide the desired flying qualities. The pressure and flow rate is typically generated by engine-driven hydraulic pumps. Backup hydraulic power may be supplied by an auxiliary power unit (APU), which is separate from the engine-driven systems, and used in case of engine failure. Most modern aircraft have dual and independent primary hydraulic power supplies leading to each actuator. They are designed to act independently in case of failure of a single system. However, when operating at this reduced capacity, the overall range of movement and rate capability is usually one-half of the nominal dual system. This can have significant deleterious impacts on the flying qualities of the aircraft. In the near future, electromechanical actuation systems may be used. These systems do away with the need for an aircraft hydraulic network and are actuated electrically. At this writing, these systems are under test. Electromechanical systems typically consist of high power electrical motors, which operate a miniature hydraulic system contained within the actuator in order to move the surface. In this sense, they are hydraulic systems, but do away with the need for a centralized hydraulic pump, reservoirs, accumulators, and associated plumbing.

The electrical power supply is critical to not only powering the aircraft subsystems, but also for powering the flight control computers and portions of the integrated servo actuators. Most systems will have a primary and secondary electrical supply Bus that distributes the power to the aircraft systems. Most of the flight critical functions are contained on a single Bus for power distribution to such items as the flight controls, actuators, and critical computers. Most DFCS systems have a battery backup to operate the flight control computers for a period of time in the case of power interruption. Like the hydraulic systems, an APU may also be used with a separate generator to supply electrical power in the event of an engine loss. This backup generator is typically much less capable than the primary engine-driven generators, and hence usually only supplies power to the critical flight functions.

The APU is a critical part of any single engine DFCS equipped aircraft. They are necessary on single engine aircraft due to relatively poor engine reliability when compared to other systems. Engine failures occur about once every 10,000 flight hours (10^{-4}/hr), which is generally a much higher failure rate than is acceptable in critical aircraft systems design. In order for the engine to not be considered a single point failure, an APU is used to supply critical power in order to recover the aircraft. The need for an APU on a multi-engine aircraft depends on the overall system design and subsystem redundancy supplied by the multiple engines.

3.3 Predict, Test, Model Update and Validate Philosophy

3.3.1 Background

Flight controls and flying qualities flight testing have traditionally used a philosophy of predict, test, model update and validation for years. The primary reason for employing this philosophy is that it has proven to be the safest and most efficient method for expanding the envelope of any new aircraft. It also provides validated models that will reduce the time and money in designing and developing future upgrades. The predict, test, update and validate philosophy is nothing more than a scientific method. Predictions are the hypothesis, test is putting the hypothesis to the test, updating is using the test results to create an improved hypothesis and validating is ensuring that the final hypothesis is valid across the range of applicability. In the case of DFCS flight testing, the hypothesis consists mainly of system models for such things as aerodynamics, mass properties, control laws, and actuation systems. Test is the combined ground and flight test program, updating is feeding the results of the tests back into the models and repredicting, and finally, validation is the process of providing valid system models at the end of the flight test program.

Virtually every model used in the initial design process is a predictive model with varying levels of accuracy depending on the prediction method used. Because of this, models can contain large uncertainties, which may show up as DFCS design deficiencies. Uncertainty and deficiencies are the primary drivers in the time and effort required to conduct a flight test program. Reducing this uncertainty, and/or discovering deficiencies as early as possible will provide the safest and cheapest test program. In today’s test environment there is a current trend in accepting increased risk in order to cut the cost of testing. This may hold true to a degree, but one only has to ask the program that has crashed a test aircraft how much money they saved by accepting increased development risk. The financial cost of the aircraft, delayed schedules and political costs of a major accident can often far outweigh the savings projected by skipping steps in the predict, test, update and validate philosophy. Fortunately, today’s computer technology allows significantly increased ability to implement this test philosophy in a rapid and cost-effective manner. Benefits from the use of modeling and simulation (M&S) have been known to the FCS community for many years, and its use will significantly increase in future years. The current push towards increased use of M&S in testing is nothing more than implementing the predict, test, update and validate philosophy across a wider range of disciplines.

There are four basic ways in which this philosophy can reduce risk and schedule. The first way is that the philosophy begins on the ground, helping to find problems early and in a safe environment. Many problems with integration, structural coupling, and erroneous code can be found before flight. The second way the philosophy reduces risk is by incrementally updating predictive models, and using the knowledge to extrapolate to future tests, again in an attempt to preempt potential problems. The third way the philosophy enhances the overall safety and efficiency is by insuring updated models for correcting deficiencies when they arise. Using updated and validated models to correct deficiencies reduces the uncertainty in any redesign effort. This not only applies for an envelope expansion program, but is also valid over the life cycle of the aircraft. Future upgrades can be made with less uncertainty and cost when using validated models. The final area the philosophy helps is in reducing the need for certain tests. Many tests are too hazardous or expensive to perform. This type of testing can often be accomplished using validated models and simulation.

Modeling and simulation use in applying the above philosophy has been used to varying degrees for years in flight control development and testing. The prediction portion of the philosophy has been a major player in flight control development for years. Unfortunately, the application of the philosophy often ends at this stage. The practice of testing, and specifically testing to update and validate models is not widely embraced. There is often every intention of updating and validating models, but this often goes by the wayside under the pressures of conducting and producing flight hours as opposed to test results. Experience has shown that one of the prime reasons for not pursuing an intended philosophy such as described here is the lack of preparation. If a test program plans to use the predict, test, update, and validate philosophy, then the DFCS flight test team must become involved early in the project. They must ensure that the proper tools, tests and schedule are available to be implemented. Without this early involvement, the best intentions to use the philosophy will not be realized. Preparation and planning are required early in the development cycle to ensure that the process will proceed.

3.3.2 Predictions

Prediction is an area where most military airframe contractors excel. This is especially true for major new development programs, which have modern resources available. Prediction may not be as sound if dealing with an upgrade of an older or existing system, or if it is an off-the-shelf acquisition of a commercial system. Historically, the general aviation community has not had the resources to do extensive predictions. As an example, one would be hard pressed to find a predicted or validated simulation aerodynamic model for a Cessna 150. Similarly, validated models for older aircraft may not be available, and the original wind tunnel or other predictive data may be long lost. The ability to adequately predict expected performance is wholly dependent on models and the fidelity of these models. This does not mean that predictions are not worthwhile if high fidelity or validated models are not available, it simply means that the predictions will have greater uncertainty, and that this must be accounted for in the test program.

The first step in the prediction process is to determine what models have been generated, what is their source, and some assessment of their fidelity. As an example, a major military airframe contractor may have thousands of hours of wind tunnel testing behind their aerodynamic models, while a general aviation contractor may only have estimated aerodynamics based on empirical methods. The level of fidelity is obviously different between the two methods. Models are absolutely necessary for the design of any full authority, fly-by-wire DFCS, since the system cannot be properly designed without these. The need for predictive models may become less necessary if the DFCS being designed is a low-gain, outer-loop system such as a simple wing leveler autopilot for general aviation aircraft. In this case, since the system does not fully control the entire stability and control aspects of the aircraft, and can be readily disengaged, then simply installing, testing, and adjusting components empirically may suffice. This is not necessarily the best or most efficient way to proceed, but until recently it has been the only way to do the job for many of these type systems. However, today’s cheap computer power, combined with a myriad of predictive software, makes this a case of not willing to invest the time and effort as opposed to a case of not being able to do the analysis.

The required predictive models vary with the complexity of the system; however, there are a few major models which the DFCS test team will require to adequately perform or participate in the predictive task. These models are: aerodynamics, mass properties, control laws, actuator and expected time delays. The aerodynamic mass properties and control law models are the most vital, followed by the actuator models. Aerodynamics are usually predicted via wind-tunnel tests, past flight tests, or by empirical methods. The level of uncertainty in the aerodynamics is possibly the biggest potential problem for the DFCS test team. The mass properties models usually have about a 10- to 15-percent uncertainty; however, the level of uncertainty is reducing as sophisticated CAD systems are increasingly being used for design. The final gross weight and cg properties can be verified by weighing the actual aircraft prior to flight. The inertias will tend to maintain their predictive level of uncertainty since adequate techniques (except in a few instances) for measurement are not available. The control laws are usually known from the design effort, but are only as good as the aerodynamics. The actuator models and time delays can be ground tested prior to flight, and while accurate models may not be available early on in the process, the DFCS test team should attempt to validate and update these models from the results of ground tests prior to flight.

The next step in prediction is to assemble component models available into a model of the system, then use this model to predict performance. Following this, the models should be placed into some form of simulation from which the predictions of performance are generated. The simulation may be as complex as a full man-in-the-loop mission simulator or as simple as using a few stability and control derivatives, a piece of paper and a pencil to predict the Dutch-roll natural frequency.

The importance of having simulation capability at the test site cannot be over emphasized. The DFCS test team is responsible for the successful and safe completion of the test program. The ready availability of simulation to predict and to compare with actual test results is vital to this function. Many program managers or contractors do not fully appreciate the benefits of on-site simulation to the success of the test program. The DFCS engineer must often work hard to convince program management of the benefits of on-site simulation.

3.3.3 Test

The testing process is where the data are collected not only to verify system performance, but also to start updating and validating system models. Attention must be applied to the types and quality of tests to not only ensure the appropriate data are collected to verify system performance, but also that appropriate data are collected to be able to update and validate final models. Specific test techniques are often required to perform model updating, which may not be otherwise required. As an example, simply performing classical flight test maneuvers may not provide sufficient information to update the aerodynamic model. Specialized test inputs may be required to adequately define the system aerodynamics from flight. Many of these maneuvers, such as separate surface inputs, may not be necessary to evaluate the overall system performance, but may be absolutely necessary to adequately define the aerodynamics.

Implementing the predict, test, update, validate philosophy starts with ground tests long before the flight tests begin. Adequate ground testing must be planned to ensure the correct data are obtained from which predictive models can be validated and/or updated. Sufficient time must be allowed for the proper analysis of the results and retest if necessary. Often the time crunch experienced by almost all test programs will result in skipping what are viewed as non-necessary tests; in order to meet the bare minimum of requirements on schedule. This can often be alleviated by early planning and scheduling in order to allow for sufficient time to perform the testing required to implement the philosophy.

3.3.4 Updating

Updating predictive models is the foundation for adequately applying the predict, test, update and validation test philosophy. Without this portion of the philosophy, additional risk and inefficiencies will be experienced by the test program. The test team must ensure that the preparations are in place to adequately employ the updating process. The DFCS test team will most likely be involved in updating aerodynamic models from flight test as well as any control law or subsystem models. The key to updating the models, which are based on the test data, is early preparation. The DFCS test team must decide which models will require updating from both ground and flight tests. They must then ensure that provisions are made in the models to allow for updating. For example, most aerodynamic models are in total coefficient form, and are not easily updated with stability and control derivatives derived from flight test. The DFCS test team must devise and implement methods for integrating these nonsimilar data types.

The update process begins with the ground test; however, this work is mostly done by the design and specific ground test engineers. As with all other aspects of applying the predict, test, update, and validate philosophy, early planning is essential. In order for updating of models to be accomplished, the proper tests, data and analysis tools must be available. The DFCS test team must decide on what algorithms or methods will be used to extract parametrics and model updates from test data, and then ensure that appropriate tests are performed across a sufficient range to allow the techniques to work. In addition, the team must also postulate a model update form and some methodology to incorporate the test data into the models. In some cases, this will be straight forward, but in other cases, such as highly nonlinear systems, a great deal of thought and planning may be required. The system should then be exercised prior to the actual start of testing. If available, simulator data can provide a good data source for exercising the system.

Once flight test starts, the aerodynamic model must be evaluated and updated as the envelope expansion progresses. There are many software algorithms that have been developed over the years to estimate the aerodynamics from flight test data. These range from linear derivative estimators such as the Modified Maximum Likelihood Estimator (*Identification of Dynamic Systems, Theory and Formulation*, Reference 1) too more complex, full envelope, nonlinear model development algorithms. The advantages of the latter are that they can produce full nonlinear models and the engineer does not have to extrapolate or incorporate locally linearized data into a nonlinear model. The disadvantages are that they usually require large sets of data before the nonlinear updating can begin. The linear derivative extractors have the advantage of being able to estimate locally linear derivatives on a test point by test point basis. The disadvantages are that they are locally linearized results, and their validity at conditions beyond small variations from the test condition depend on the linearity of the system’s aerodynamics. Another disadvantage is that they must often be incorporated into a nonlinear model, which can be a difficult task. Both methods will only supply data in regions where the system is tested; extrapolation to regions beyond where tests have occurred is often up to the engineer doing the updating. When extrapolating to regions not tested (as an example to high sideslips), the wind-tunnel data can often give the engineer an indication of the general shape of the function. This shape should be followed wherever possible unless direct flight test results contradict the original shape. There is some danger that these extrapolations will not be valid. Any updated model must contain documentation which details which data are from actual tests, which are extrapolated and what the extrapolation is based upon.

3.3.5 Validating

Validation is the final graduation exercise for the updated model. The model must adequately predict system performance over a wide range of tests. Many of these tests may or may not have been used to develop the new model. The key to a solid validation is the model's ability to represent the system under test. The final validation checks must be carefully planned to account for the operating range of the systems, and to account for nonlinearities in system characteristics. As an example, just matching the response to small amplitude doublets is insufficient to ensure the model’s validity. Full amplitude maneuvers must also be matched against test data.

The target of the final model should also be considered in the final validation plan. An aerodynamic model, which will be used in an avionics trainer, may not require the fidelity and breadth as that for a full engineering level simulator. Many models for different purposes may be generated; the engineering team must decide what levels of validation are required for each model, and then design the validation effort accordingly. Both the validation process and model as a whole must be thoroughly documented. The validity range of the model must be presented in such a manner that future users will know how far the model can be trusted. As an example, a simple transfer function model of the roll dynamics of an aircraft must not be used to predict the character of a full 360-degree roll maneuver. The model documentation must contain sufficient information so that the user will not have to assume a range of validity and subsequently inappropriately apply the model.

3.4 Configuration for DFCS Flight Testing

3.4.1 General

It is estimated that 70 to 80 percent of future flight test programs will involve disciplines other than performance and flying qualities. Avionics, communication systems, defensive and offensive systems and low observability will constitute the bulk of the test program’s schedule and budget. However, before much of this can occur, the basic flight envelope must be cleared. Any delays during the performance, flying qualities and structures testing will delay the entire program. Test communities have developed special test configurations over the years. These configurations significantly improve both the efficiency and the safety of flight testing the DFCS. These special systems configurations allow a thorough examination of the system as well as enhance the ability to apply the predict, test, update, and validate philosophy. This section will describe some of these special test configurations as they apply to the flight testing of the DFCS.

One of the most difficult jobs of the DFCS test team is to convince program management of the need for these specially designed systems. They add cost and schedule up front in the design process, and as such program management is often reluctant to include them in the test vehicle. This is especially true in today’s world of success-oriented systems test, where everything is expected to work the first time. When the inevitable occurs, and the system has a problem, defining and correcting the problem may be difficult. The use of these configurations must be sold to program management on a risk reduction basis. Having these capabilities reduces the risk of ‘show stoppers’ occurring and minimizes the time for redesign if major anomalies are found during flight test. The special test configurations allow the test team to understand not only what the system is doing, but also why it is occurring. This is the first step in any problem resolution process. These configurations help to minimize or reduce risk by allowing the problem resolution process to proceed as rapidly as possible when unexpected anomalies are found during test. The new emphasis on using modeling and simulation, and hence the predict, test, update, validate methodology, will aid the DFCS flight test team in convincing management that the addition of these special configurations will have a financial and schedule return on investment.

3.4.2 Programmed Test Inputs

The programmed test input (PTI) allows insertion of test signals at specific points in the flight control system. Test signals are usually stored in the DFCS memory, and appropriate paths allowed in the initial software for implementation. The PTI is designed to provide a given set of information. It is often used to define aerodynamic, FCS functional and aeroservoelastic characteristics. Some information may not be obtainable from normal system operation and may require a PTI for model generation or validation. For example, the current practice of using correlated aileron and differential horizontal tail to provide roll control may make it impossible to separate the aerodynamic effects of each. A separate surface input may be required to identify the aerodynamics of both the aileron and the differential tail.

Although many types of inputs are used, they are usually of relatively small amplitude. Inputs such as small amplitude doublets, steps and frequency sweeps are most often used. Maneuver duration and magnitude are verified in the simulation and tailored for the configuration, test condition, and information desired. The PTI also requires some form of input limiting and failure checking. The systems are designed to disengage when failures are detected or limits exceeded. The system must also contain the ability to be engaged and disengaged by the pilot or a ground controller. Careful verification of the implementation, failure and limits monitoring, and input type must be carried out with the actual software in a bench test or iron bird implementation prior to flight. Errors in the code or implementation can have disastrous effects.

3.4.3 In-Flight Variable Gain

As full fly-by-wire systems have become more prevalent in recent years, the use of an in-flight variable gain capability has proven invaluable. This type of system has been successfully used on the B-2, C-17, F-16, F-15E and YF-22 test programs. The in-flight variable gain allows the use of a variable set of predetermined gains during the test program. All systems with a DFCS will experience some difficulty during development and will require, as a minimum, gain modifications during the flight test program. Software modification, verification, and validation are time-consuming and expensive processes. This time can be minimized by using multiple gain combinations within the same software release. The inclusion of an in-flight variable gain capability will reduce the need for expensive and time-consuming fly-fix-fly methodology. In addition, there are some problem occurrences such as aeroservoelastic instability or large amplitude limit cycle where flight safety may require a rapid reduction in gain level. This can only be accomplished with in-flight variable gain capability. The decision to use variable gain capability must be made early in the design portion of the program, since the ability must be incorporated into the test software.

The gains to be varied and the allowable sets of variation are usually determined via simulation and parameter variation studies. Potential variation sets are identified and included in the basic software. Careful software verification as well as the predicted flying qualities with each gain set must be studied prior to their use in flight; this will help preclude using a set of gains which are unsafe. It is often difficult to prejudge the desired level of gain variation prior to knowing the actual system performance. Parameter variation studies can help to identify candidate gain variations, but even as such, they may not be correct. The actual gain values can be modified during planned software update cycles to reflect actual system performance.

One of the past objections to implementing an in-flight gain variation process has been that the final software, without the gain variation path, must be completely retested or verified before final production release, thus adding expense to the program. Many modern test programs alleviate this concern by leaving the gain variation capability within the production software, but deactivate the capability in the final production release. This philosophy reduces the extent of the retest and verification process and also makes it much easier to accomplish future upgrade testing, since the basic capability already exists in the production software and does not have to be redesigned in for future upgrades. Another objection concerns the safety issue of varying the gains while in flight. The in-flight variable gain capability has mainly been used in the United States to date, and many European aviation organizations are leery of its use. There is the potential for selecting gains which could cause system problems or instabilities. Risk can be minimized by employing a carefully designed verification and prediction process. The process has enjoyed success with many test programs without major incident. The experience to date has been that the benefits out weigh the risks if the methodology is properly applied.

3.4.4 In-Flight Fault Simulation and Clearing

An in-flight fault simulation and clearing capability makes it possible to evaluate the flying qualities of failure states. Implementing simulated failures along with the ability to quickly clear them also allows final validation of the redundancy management process. As in other in-flight modifications of the DFCS, the type, location, and capability to accomplish clearance must be carefully verified and validated prior to its actual use in flight. There continues to be much disagreement within the DFCS test community as to whether it is wise to provide this type of capability in the test vehicle.

Most DFCS allow for the detection and isolation of failures, as well as providing appropriate re-configuration when failures degrade system performance. Testing of failure states has mostly been left to simulation in the past. There are certainly some failures for which it is too dangerous to investigate in flight, and these will require verification and validation via simulation. However, the situations where the flying qualities are not predicted to be unsafe can be verified in flight using this capability. This is most applicable within the fail operational levels of fault detection or with outer loop systems such as autopilots, which can be quickly disengaged. In addition, it is likely that at least some unintended failures will be encountered during the test program. Many of these failures are momentary problems, which may have been latched or locked into place by the software. The fault may be self-correcting, but the aircraft has been placed in a reduced state of safety by latching the failure into place (i.e., a sensor is still declared failed when properly operating again). If this is the case, the ability to clear a fault may succeed in placing the aircraft back into a full operational status. An example may be an air-data probe failure while momentarily at high AOA or sideslip. A fault may have been declared and latched and the backup gains invoked, however, the air data system may well return to normal operation after recovery to lower AOA or sideslip. If the failure has been latched, the system may remain in a backup gain mode. The ability to clear this type of fault will save test time and complications, as well as improve test safety.

3.4.5 Instrumentation

Perhaps the most important part of a proper configuration for flying qualities testing is the instrumentation system. The DFCS flight test team must be actively involved early in defining this aspect of the configuration. While the design engineers may also be instrumental in defining needed parameters, most have little or no knowledge of instrumentation system operation. It is up to the test team to supply this knowledge to ensure that not only the appropriate parameters are available, but also that the quality of the instrumentation is satisfactory. Unfortunately, the tendency is to assume that if a parameter is instrumented, then the quality is sufficient to supply the needs. This is far from the truth. The quality of the instrumentation can make or break the use of a predict test, update, and validate test philosophy. The ability to apply this philosophy is only as good as the instrumentation, both in the parameters available and the quality of the data.

The first step is to decide which parameters should be instrumented. These need to include internal DFCS and other systems parameters, which may be needed to quantify the system. The test team should look at the intended envelope of the aircraft, what the test objectives are, what level of model updating and validation is planned, and the data analysis methods. Current instrumentation systems are capable of providing a large number of parameters at significant sample rates. However, just because a system can do something, does not mean that it should. There is a tendency to request many more parameters than are needed. This not only adds unnecessary cost to the program, but can also adversely impact the truly needed information. The DFCS flight test team should judiciously determine the required information for the program, and resist the tendency to ask for more than they need.

The next decision will be parameter range and resolution. Range and resolution are integral parts of each other, since almost all-modern data systems will eventually undergo digitization. The range and bit level of the digital words will determine the resolution. The range must be carefully considered, and appropriate values selected which reflect the aircraft performance capability. For example, it makes no sense for the air-data instrumentation system on a subsonic transport to have the ability to read Mach numbers up to 2.0. Another example might be pitch and roll rates, where a transport aircraft would not be expected to experience as large of values as on a fighter. The resolution will be determined by the overall range and the least significant bit capability of the digital word. Large ranges, combined with low bit length words will provide poor resolution. As a rule, the minimum word length for most flying qualities testing should be 10 bits, with 12 or more desired. As an example, the resolution with a 10-bit-word length on roll attitude, with a 360-degree range will be approximately 0.36 degrees. The following formula can be used to determine resolution from bit length and range.

$$\text{Resolution} = \frac{\text{Range}}{2^n} \tag{2}$$

where:

n = number of bits.

Resolution should not be confused with accuracy. Just because the resolution of a measurement is known, the same level of accuracy is not necessarily present. Resolution only gives the smallest variation the sensor can measure. The accuracy of the measured parameter or parameters depends on several other factors, particularly resolution, calibration, and corrections. As an example, an AOA vane may have a resolution to 0.1 degree, but other error sources in the measurement (e.g., upwash, rate errors), will mean that the accuracy is much less.

Sensor placement should also be considered. Sensor placement can be critical, but is primarily a matter of available locations and common sense. Using a noseboom on a single engine, tractor propeller-driven aircraft will not be possible and a total temperature probe in the exhaust stream of the engine will not provide accurate data on the free stream air temperature. Space, power and cooling availability, structural modes, and wiring placement will all play a role in where sensors can be placed. The DFCS flight test team should seek to ensure that within bounds of practicality, the sensors are placed as close as possible to where accurate data can be measured.

The next consideration is sample rate. Theoretically, Nyquist theory states that a minimum sample rate of twice the highest frequency of interest is required to identify that frequency. In practice, the rule of thumb is a sample rate 4 to 5 times the highest frequency of interest. This is a rule of thumb and not always applicable. For example, for aerodynamic parameter identification, where frequencies higher than 5 Hz are almost never encountered, a sampling rate minimum of at least 40 samples per second is desired. Lower rates can be used if the system is precisely timed and noise or delays are minimal. This is not the case with most data systems. For most flying qualities work, the key parameters should be sampled at a minimum 40 to 50 samples per second. These include accelerations, angular rates, attitude, AOA, sideslip, and surface and pilot inputs. Airspeed, altitude, and weight measurements can be taken at lower rates, but should be at a minimum of 10 samples per second. High sample rates should also be used for internal analog signals for such things as actuator commands and hydraulic pressures. The internal DFCS parameters should be minimally at the rate of the frame time for the computer, although a higher rate may be desirable to ensure that discretes are registered accurately.

Whenever digitization of any analog signal is applied, aliasing must be considered. Aliasing is a high-frequency signal that appears as a low-frequency signal when digitization is applied. All analog signals will contain frequencies higher than those required for the basic parameter of interest. For example, high-frequency structural modes may be present in an accelerometer signal. These frequencies may be much higher than the desired rigid-body motion being analyzed. If appropriate precautions are not taken, these frequencies can alias and appear as lower-frequency rigid-body motions. Once aliasing occurs in a digital signal, there is no recovery unless the analog signal is available. Since most sensor signals are analog prior to being digitized, the solution to aliasing is to low pass filter the analog signal prior to digitization. These are called anti-aliasing filters. They work by attenuating higher frequencies in the analog signal so that the impact of aliasing is minimal. Aliasing cannot be prevented, but its impact can be reduced so that it is no longer a factor. Digital filtering after digitization will not remove or reduce the impact of aliasing. It is obvious that the type of filter, its cutoff frequency, and roll-off characteristics can have a profound impact on the quality of the test data recorded. The DFCS flight test team should familiarize themselves with the basics of anti-aliasing filter design and implementation.

Whenever filters are used on any signal, phase lags are invariably imparted. Relative phase lags between signals are extremely important, particularly when performing parameter estimation. Most parameter estimation techniques use the relative phasing of signals for the identification process. Artificial relative phasing induced by using mismatched filters on signals can lead to misidentification of parameters. For this reason, signals, which will be used in any model updating or parameter identification analysis, should use the same anti-aliasing filters. While all will experience phase lags, the relative phasing will remain unchanged.

Another factor impacting relative phasing is time delays. A pure time delay will lead to phase lags; the amount of phase lag is proportional to the frequency for a given time delay. Relative time delays between signals can be induced with the practice of using multiple computers to shunt signals to their final destination, the data recording system. Perhaps the worst offender in introducing relative time delays is the often used 1553 data bus. The data are placed on the bus in an asynchronous manner, and there is usually no way of telling when the data were actually sampled. The data system may know the time the data were retrieved from the data bus but has no way of knowing when the data were actually sampled and placed on the data bus. The asynchronous nature of the 1553 bus also means that the delay will not be consistent, hence cannot be measured on the ground and later corrected. Modern practice is to use the 1553 or similar data bus for all data transporting. This can impact parameter identification and model updating. The DFCS test team should try to ensure that parameters, which would be used in the model updating, would not be obtained over a 1553 data bus. However, this is not always practical since almost all modern data systems use the 1553 data bus architecture. In this case, having high sample rate or time tagged data may reduce the relative time delay impacts between signals.

3.5 Ground Testing

3.5.1 Background

Ground testing covers a broad range of tests and analyses in order to provide information to enable system design and the verification and validation of system operation prior to flight. Ground testing experts primarily conduct many of these tests, such as wind-tunnel or ground-vibration testing (GVT). However, the DFCS test team can add either personal or corporate experience to the process in order to aid in the design of the tests. Past experience on problems encountered with mispredicted models can be extremely beneficial to the professionals involved in these areas. There are other tests such as aeroservoelasticity (ASE) or rigid body limit cycles where the DFCS flight test team may become personally involved in the conduct and data analyses. Proper ground testing is essential in helping to ensure the success of the flight test program.

3.5.2 Verification and Validation Testing

Verification testing is the process of determining if the system is designed as specified; does the software or hardware perform as specified? Validation testing is the process of determining if the system, as specified, will perform the intended task. A system can be verified, but the overall performance will not satisfy the requirements. That is, systems can be verified and all systems perform as specified, but still not be validated. The distinction is not always obvious, but a loose analogy might be that all the subsystem components operate as designed, but when combined into an entire system, they do not perform the intended task.

Figure 2 shows a simplified block diagram of the DFCS verification and validation (V&V) process. Validation and verification are performed on both the software and hardware. Testing usually begins at a subcomponent level, and then proceeds to the combined systems level in steps. Each subcomponent, such as actuators, hydraulic pumps, software modules, is individually tested to ensure that they are performing as specified, then systems are combined to ensure that they work together to provide the desired performance. Software testing is particularly complex, and often takes up the majority of the V&V time. For this reason, much of the module level and even combined level of software verification testing is currently automated. Software V&V is an area that will impact the DFCS test program throughout the development cycle. Extensive software V&V may be required for even small software changes to ensure that the signal or information flows have not been altered.

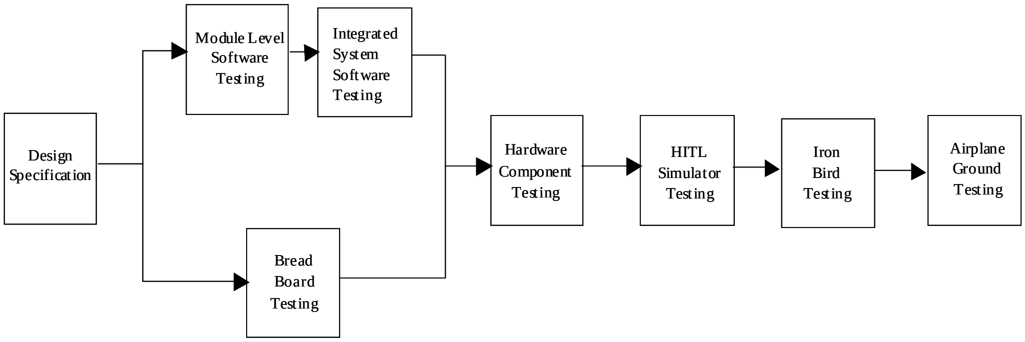

Figure 2 Simplified Digital Flight Control System Ground Test Verification and Validation Process

3.5.3 Wind-Tunnel Testing and Aerodynamic Modeling

Perhaps the earliest and most invisible ground testing to the DFCS flight test team are the wind-tunnel tests. Wind-tunnel testing is normally perceived as the province of the aerodynamacists and wind-tunnel testing experts. However, errors in the wind-tunnel data or development of the aerodynamic model from these data tend to cause the DFCS flight test team some of the most common and troubling problems during the flight test program. The most valuable contribution the DFCS flight test team can make to these efforts is historical information from past programs relative to troubles encountered. Data on specific wind tunnels and their known error sources, data on where past aircraft have had difficulty in predicting the aerodynamics, and known past modeling errors, can be invaluable to the developers of the wind-tunnel tests and aerodynamic models. This knowledge is often available either from personal experience of the DFCS flight test team, or within other areas of the flight test organization

The DFCS flight test team should make themselves familiar with the types of tunnels used, the techniques employed and where the data from these tests are applicable. They should also become familiar with what tests were run, the model configurations, and the basic test matrices. If involved early, the DFCS flight test team should review the planned tests for completeness. The wind-tunnel testing should cover not only the operational envelope, but also the planned test envelope. For example, if spin flight testing is planned, and the wind-tunnel testing does not include rotary balance data, the test team should suggest that this type of testing be conducted.

The DFCS flight test team should also become familiar with the process being used to generate an aerodynamic model from the wind-tunnel data. Today’s aircraft usually undergo thousands of hours of wind-tunnel testing to define the final configuration. The volume of data alone makes it impossible to simply lump all of the wind-tunnel information into a large table lookup model. In addition, much of the data may be for preliminary configurations, with subsequent wind tunnel runs used to define changes based on configuration updates. It is usually up to the aerodynamacist to combine all the data into a usable aerodynamic model. This is a job that requires experience and judgment and hence is prone to adding human modeling errors to the errors in the wind-tunnel data itself. The adequacy of the wind-tunnel testing and the aerodynamic modeling will be the cornerstone of the DFCS design and test effort. Inadequate wind-tunnel testing and modeling will increase the uncertainty in the system, and most likely lead to design and flight test problems.

3.5.4 Initial Piloted Simulation

Once a reasonable aerodynamic model is available, the initial control law design can progress. Once an initial control law design is available, a simulation can be constructed to evaluate the effectiveness of the design. This will range from small amplitude linear simulations to more complex six-DOF, nonlinear simulations. The initial control laws are usually digitally modeled in an interim language such as FORTRAN or C, along with models for the aerodynamics, mass properties, actuation systems, and sensors. Modifications are based on simulation results then progress until a final control law configuration is defined. Simulations (linear, reduced DOF and 6-DOF nonlinear) are integral to the design process for a DFCS.

Once a DFCS configuration is available, more complete testing for flying qualities is conducted with a piloted, 6-DOF simulation. This testing will cover the entire envelope and encompass stability, control, and handling qualities. The goal is a final verification that the proposed control laws will meet the specifications. At this point, models for the RM and other system digital models may or may not have been added to the simulation. If the RM system is modeled, failure mode testing may begin at this point as well. There is a tendency to fine-tune the system as the piloted simulation testing nears its final stages. This may or may not be a problem, depending on the type of simulation and the fine-tuning being accomplished. Pilot opinion is critical in defining the final control law configuration, but this opinion can also be in error. As an example, it is common for pilots to think that the aircraft is sluggish based on fixed-base simulation results. Fine-tuning so that the pilot now feels the system responds ‘just right’ may well result in a design that is overly sensitive in flight. The fixed-base simulation does not provide the pilot with the seat-of-the-pants cues for maneuvering (as will occur in flight), hence the initial perception of sluggishness based on fixed-based simulation may be incorrect. The use of a motion-based simulation is controversial in solving this problem. Limitations of motion-based simulations mean that they cannot duplicate the aircraft motions with a high degree of fidelity. They may provide motion cues, but the results based on these cues can be as much in error as using the fixed-based simulator.

Another controversial subject for this level of evaluation is handling qualities. Because of the limitations of ground-based simulation, it has long been held that handling qualities evaluations for problems such as PIO or poor task accomplishment cannot be accomplished on the simulator, and especially not on a fixed-base simulator. The limitations of ground-based simulation, motion infidelity, time delays, and lack of visual acuity have long been thought to preclude ground-based simulation use in handling qualities studies. While detailed handling qualities and fine tuning may not be possible, it has been the experience at the Air Force Flight Test Center (AFFTC) that major handling qualities problems such as severe PIO can often be detected on fixed-based simulation using simple visual displays. The key to success is to eliminate motion, minimize visual-time delays and conduct a sufficiently high-gain task. High fidelity visual scenes are often reduced to simple stick diagrams mimicking an attitude directional indicator (ADI) in order to reduce visual time delays. A high-gain, zero error, random tracking task such as handling qualities during tracking (HQDT) (*System Identification Form Tracking,* Reference 2) is performed to search for major problems such as PIO. This is a specific task as outlined in Reference 2 and is different from normal operational-type tracking. While techniques such as these may reveal severe handling qualities problems, the overall lack of ground-based simulation fidelity also makes fine-tuning of handling qualities questionable. Trying to go from a Cooper Harper Rating (Reference 3) of 2 to a 1 is probably not within the fidelity of the simulation. However, going from a 7 to a 3 may be possible if the tasks are properly designed.

An important study, which is appropriate at this stage, is aerodynamic parameter variation evaluations. This study is often planned, but quickly goes by the wayside as programmatic pressures build. As previously discussed, the aerodynamic model is an area of relatively high uncertainty, and is a key component to any DFCS control law design effort. Most systems are designed to be robust; however, classical measures of robustness such as gain and phase margin do not necessarily give sufficient insight neither into nonlinear behavior nor to the flying qualities of an aircraft. It is advisable to vary the key aerodynamic parameters from 25 to 50 percent, in a worst case direction, and then re-evaluate the flying qualities with piloted simulation.

3.5.5 Module and Integrated Software Level Testing

Once the final system design has been established, the process of coding the final system software begins. Verification testing of the software operability is one of the most time-consuming and expensive processes in the design cycle. Many tests must be repeated any time that software is updated. While testing may begin early in the design process, verification must be conducted with the final design intended for flight. The software verification process is designed to verify that the software is working according to specification. Code for most modern DFCS systems can run into hundreds of thousands of lines, and the complexity increases as more and more integrated systems are being designed. As code complexity increases, so does the software verification task.

Most control system software is modularized to make integration and modification easier. To ensure the correct operation of each module, verification testing is conducted. This testing is often automated, with preprogram inputs to the module designed to verify all input and output paths, as well as internal module paths. Once the module level testing has been accomplished, the modules are assembled to perform higher level functions, and the detailed testing is repeated. The modules are then assembled and compiled into the target flight control computer (FCC) and verification testing is repeated.

3.5.6 Hardware-In-The-Loop Simulator

The hardware-in-the-loop (HITL) simulator is a hybrid simulator, which at its simplest level contains the DFCS and other computer hardware with the associated software. The simple level HITL simulator usually does not contain hydraulic, electrical or actuation systems. The purpose of this level of HITL is to verify that the software implementation acts as designed within the actual FCC hardware. The control laws and commands are generated via the actual FCC; the input signals, actuation commands, and resulting aircraft motion are generated via digital simulation.

3.5.7 Iron Bird

The Iron Bird is a higher level HITL simulation where all the flight control hardware and software are integrated with the actuation, hydraulic and electrical power systems, and sensors. The 6-DOF dynamics are simulated via digital simulation. The systems are duplicated exactly as they will appear on the aircraft. The simulator should also model the mass properties (e.g., weight, cg, and inertias) of the control surfaces. The Iron Bird should contain all of the mechanical and electrical nonlinearities as the full aircraft systems. The system should be capable of simulating the rigid-body dynamics and resultant hardware and software response as close to that of the actual aircraft as possible. Sensor inputs and dynamics are usually simulated either digitally or in analog form.

The Iron Bird simulation is used to verify and validate the rigid-body, total-system models and design. At this stage, the system will be well enough defined to allow both verification and validation testing. Extensive software, logic, static and dynamic verification testing will be conducted on the integrated flight control, hydraulic, and electrical systems. Validation testing on actuator, hydraulics, and electrical system components will also be accomplished. The Iron Bird is as close a simulation as is possible of the aircraft systems and subsystems as can be accomplished prior to having an actual aircraft.

Most modern military and commercial aircraft programs will have an Iron Bird available for not only the initial development testing, but often well into the life cycle of the aircraft. During the life of an aircraft, many software and hardware upgrades and modifications can be expected, which will require the use of an Iron Bird. However, many small programs, or upgrades on older aircraft, may not have the benefit of an Iron Bird simulator. It may be necessary to conduct the tests with the actual aircraft. There are advantages and disadvantages to this process. The advantage is that you are working with the actual hardware, and not a simulation. This will increase the confidence level in the results. The disadvantage is that the aircraft can be damaged if instabilities are encountered during the tests. For this reason, a kill switch which will rapidly cutoff hydraulic or electrical power is a requirement for on-aircraft tests. Another disadvantage of on-aircraft tests is the necessity to use a hydraulic and electrical cart to provide hydraulic and electrical power to the aircraft. These carts seldom have the full hydraulic flow capacity of the real aircraft system. Data on the nonlinear characteristics, such as surface rate limits where hydraulic flow capacity is critical, may not be valid for tests using a cart as a power source.

3.5.8 Ground Vibration Tests

The ground vibration tests (GVTs) are performed by the structural dynamics engineers to validate the analytic structural models used in the design. Special excitation devices are used to vibrate the aircraft structure at frequencies which span the spectrum of the predicted modes. An array of accelerometers attached to the surface of the aircraft measure the response to a known input. The structural dynamics engineers can then experimentally determine the frequency, amplitude and mode shapes for the structure. The GVT results are used to update the predicted structural models of the aircraft.

The GVT results are more accurate than analytically predicted characteristics, but also have some level of uncertainty. One source of uncertainty is the type of ground support system. The manner in which the aircraft is structurally supported can impact the results of these tests. If the aircraft is sitting on the landing gear, the measured modes may be impacted by the dynamics imparted by the gear and interaction with the ground. Several solutions to this problem have been used in the past. These range from deflating the landing gear struts and tires to using complex and expensive soft support systems. Determining the ground support requirements is a complex subject, which will be decided by the structural dynamics experts.

The DFCS flight test team may or may not be directly involved with the GVT. However, if not involved, they should be aware of the results, and whether or not the results validate the analytic models. Closed-loop flight control systems can interact with the structural modes and cause instabilities. If the test results are significantly different than those predicted by the analytic models, than serious flight control problems could occur.

3.5.9 Closed- and Open-Loop Structural Resonance and Stability Margins

Closed-loop flight control systems can couple with the structural dynamics and cause severe instability. Structural coupling, or resonance, can cause catastrophic failure and loss of the aircraft. Structural resonance tests are conducted to validate the analytic models for the final closed-loop system. Stability margins are measured to ensure that coupling has been sufficiently suppressed or does not occur. For most of the history of the DFCS, structural coupling has been primarily a concern in frequency ranges outside of the rigid-body dynamics (i.e., modes greater than 4-5 Hertz). This allowed the structural resonance ground tests to be conducted without accounting for the rigid body aerodynamics; hence, the tests could be performed without the need for inclusion of these dynamics in the loop via digital simulation. It was possible to separate the structural coupling tests at high frequencies and the lower frequency tests for rigid-body limit cycle, which will be discussed later. This situation is still true for many structurally stiff fighter-type aircraft, but may not be true for larger transports, which tend to have lower structural frequencies. This may change for fighters as active structural control is used instead of the heavier structural stiffness to control loads and dynamic modes.

Until recently, notch filters on the sensor inputs were the primary tools for ensuring that structural modes did not couple with the DFCS. Structural mode motions picked up by the DFCS sensors were reduced or eliminated with notch filters, which removed the structural component from the signal. This method is called gain stabilization, where the highest structural peak in an open-loop frequency response was at least 6 to 8 Decibels (dB) below zero dB (dB is defined as $20*\text{Log}_{10}[\text{output/input}]$). Linear analysis theory states that the boundary for stability is where the gain is at zero dB and the phase is $\pm$180 degrees. The notch filters attenuate the structural component of the feedback signal to ensure that the gain at the structural frequencies of concern was at least 6 to 8 dB away from instability. This method has worked well with structurally stiff fighter aircraft, which were the primary users of the DFCS for many years. The structural stiffness ensured that the modes were of sufficiently high frequency so that deletion from the feedback loop would not impact the rigid body flying qualities. However, full fly-by-wire DFCS is now being used on larger aircraft. These aircraft typically can have structural modes which are at low enough frequencies to limit the use of notch filtering across the frequency spectrum. Notch filters can be used for the higher frequency modes, but the low frequency modes may be well within the rigid body flying qualities frequency range, precluding the use of notch filters. When this occurs, extreme care must be taken in the DFCS design to ensure that a coupling instability does not occur. This can be accomplished by ensuring the system loop gain remains relatively low, and in conjunction with a methodology called phase stabilization. In phase stabilization, the system is stabilized by using appropriate filters to shift the phase curve away from the $\pm$180-degree point to ensure that instability does not occur.

Structural resonance testing is often referred to as ASE testing. This is not strictly true since the aerodynamics are not always considered, making the structural resonance servo-elastic, as opposed to aeroservo elastic tests. The aerodynamics come into play in two areas, the rigid body aerodynamics which are usually considered for frequencies below 4 to 5 Hz, and the unsteady aerodynamics associated with flutter, which come into play above approximately 3 Hz. The unsteady aerodynamics are difficult to predict and model, and are therefore difficult to add to any digital simulation for full ASE testing. Experience has also shown that the unsteady aerodynamics tend to add damping to the system, and therefore, neglecting these during the ground structural resonance testing will usually give conservative results. For these reasons, if the structural modes of interest are of sufficiently high frequency, aerodynamics is often not included during the structural resonance tests.

Figure 3 shows the schematic for the open-loop structural resonance tests. The system is first tested open loop as a buildup to minimize encountering a potentially damaging closed-loop resonance. For these tests, a sin wave frequency sweep is input at the sensor location, and the response is measured at an output. This is done a single loop at a time, often with other loops remaining closed. Care must be taken to ensure that instabilities do not occur in the closed loops. Determining the correct input and output sources to define the true open-loop characteristics depends on the system. Special test versions of the DFCS control laws may be used to allow loop opening within the control laws themselves, or if this is not available, then other input/output points such as at the actuator command junction may be used. The frequency sweeps start at low magnitude, and then are run with increasing magnitude to check the impact of nonlinearities on the response. The input and output signal are analyzed with a Fast Fourier Transform (FFT) algorithm to obtain the spectral characteristics and Bode or Nyquist plots. Actual gain and phase margins can then be measured from these plots.

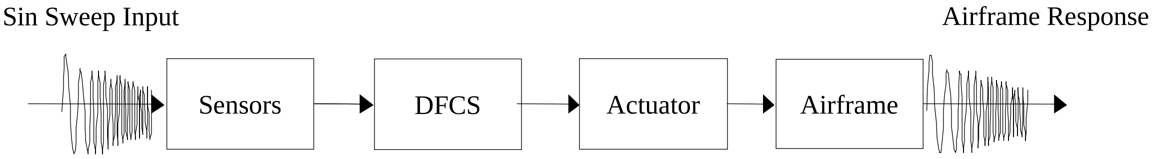

Figure 3 Open-Loop Structural Resonance Schematic

Closed-loop tests are conducted after the open-loop tests show sufficient margins. Figure 4 shows a schematic for the closed-loop tests. For these tests, the loop is closed, and the structure is excited with high frequency inputs. The response is monitored to ensure that an unsafe resonance does not occur. For these tests, the loop gain is incrementally increased to a magnitude 6 to 8 dB above nominal to ensure that resonance does not occur. This gives the final validation that sufficient margins are present in the system.

For both the closed- and open-loop resonance tests, the DFCS configuration is important. The DFCS must be configured to ensure that the gains being selected are representative of the intended flight condition. This may require that special test equipment to provide appropriate air data inputs (airspeed, Mach number, altitude, AOA, etc.,) such that appropriate gains and logic paths are used. Gain combinations are important, the DFCS flight test team should ensure that the areas of highest loop gain in terms of airspeed, altitude, and AOA have been covered during the tests.

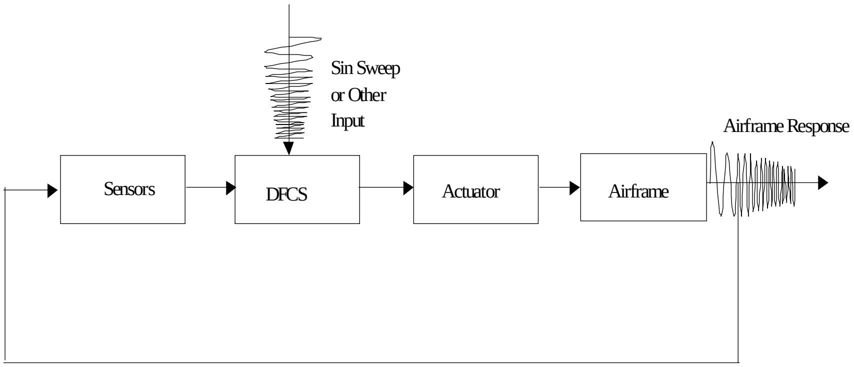

Figure 4 Closed-Loop Test Schematic

3.5.10 Rigid Body Limit Cycle

The purpose of the rigid body limit cycle tests is to evaluate the impact of control system nonlinearities such as hysterisis and dead bands on the system gain margins. Nonlinearities are present in all control systems, although careful design has attempted to minimize their impact. As previously discussed, the unsteady aerodynamics are not included due to prediction and modeling difficulties; however, the rigid-body aerodynamics are included in the loop. Rigid body limit cycle is usually concerned with frequencies of 3 Hz or less, hence the importance of not including unsteady aerodynamics will be reduced but not eliminated. There will still be uncertainty in both the predicted rigid-body aerodynamics as well as the impact of unsteady aerodynamics.

Figure 5 shows a typical test set-up for rigid body limit cycle testing. The sensors, aerodynamics and aircraft response is computed via digital or analog simulation. Removing the sensors from the loop essentially removes the structural aeroelastic coupling response from the test. The tests are usually conducted with the aircraft resting on the gear, and appropriate measures taken such as deflating the tires and struts. However, the tests can also be run in conjunction with the structural coupling tests if provisions are made to include the required simulation and connections. This method is increasingly used with the sophisticated simulation capability available today.

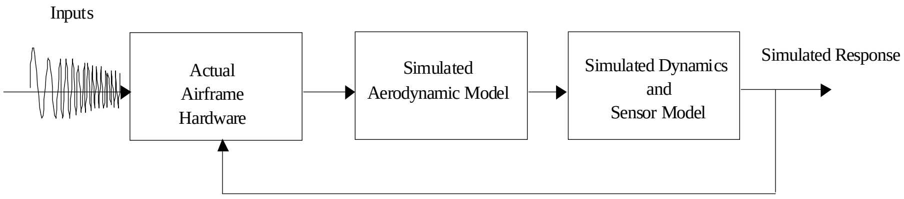
Inputs
Actual Airframe Hardware
Simulated Aerodynamic Model
Simulated Dynamics and Sensor Model
Simulated Response

Figure 5 Rigid Body Limit Cycle Schematic

Rigid body limit cycles tests are accomplished with an increasing gain method. The loop gain is incrementally increased until small amplitude oscillations occur, or an increase of 8 dB without sustained oscillation has occurred. Because rigid body limit cycle can cause structural damage if the amplitude is allowed to get too high, a hydraulic kill switch should always be available. Likewise, careful prediction from digital models including all known nonlinearities as well as test data from the Iron Bird should be used to define the test matrix. Small gain increments should be used when approaching regions of predicted limit cycle to minimize the possibility of large amplitude or divergent limit cycle.

Since limit cycle is a nonlinear phenomenon, linear analyses will not necessarily predict the proper margins. Designers typically try to minimize the nonlinearities present in any system, but elimination of these nonlinearities is impossible. All mechanical systems will experience some degree of dead-bands, hysterisis, and freeplay. In some cases, the specific use of nonlinearities is beneficial to the FCS performance and intentionally designed into the system. In general, the nonlinear gain margins will be lower than the analytical linear margins; hence, limit cycle may be encountered at a gain increase less than that indicated by linear analysis. Limit cycle is a function of the total loop gain, which includes aerodynamics as well as FCS scheduled gains. The test conditions for the rigid body limit cycle need to reflect regions of the maximum loop gain considering both the DFCS scheduled gains and the aerodynamic contributions, which are proportional to dynamic pressure. The FCS usually decreases gains with dynamic pressure to offset this increase in the aerodynamic gain; however, this is not always the case. Fixed gain systems or systems where other factors change the loop gain (e.g., AOA) can result in increasing the overall loop gain with dynamic pressure.

3.5.11 Electromagnetic Compatibility

Electromagnetic interference (EMI) represents a serious problem for an electronic flight control system since it provides a mechanism for potential common mode failures in a multiredundant DFCS. Malfunctions caused by EMI can range between being insignificant in nature to causing catastrophic failures. Electromagnetic interference can be both internally and externally sourced and the DFCS design process must address these issues. The FCCs, control surface actuators, and sensor units (inertial, air data,) as well as all pilot inceptors, switches, and all data-bus inputs and wiring associated with the FCS must be designed to be resistant to all forms of EMI. This will include radio frequency (RF), microwave, lightning and electromagnetic pulse (EMP) sourced interference as well as any perceived future EMI threats.

Before the aircraft's first flight is flown, sufficient electromagnetic compatibility (EMC) testing must be performed on the complete aircraft to ensure that the aircraft is safe to fly in the local electromagnetic environment. As the test program continues, EMC testing to clear the aircraft to the full electromagnetic threat levels in the production configuration must be performed

The EMC ground test program must be an integrated part of the overall EMC test philosophy for the aircraft and its equipment since the aircraft test results will be used, along with the equipment test results, to demonstrate adequate margins from malfunction. When defining the aircraft test program, it must be ensured that the aircraft and its systems are in a representative condition for each phase of the EMC test program. In particular, the aircraft must be in a fully flight representative condition for the final phases of on-aircraft EMC testing. This will ensure that the test results are valid and realistic flight clearances can be generated.

There is a variety of EMC test techniques currently used on aircraft with a DFCS. Initial on-aircraft testing will commence with the aircraft in an unpowered condition and either single-loom or multiloom bulk current injection tests may be performed. External antenna can also be used to radiate the aircraft at a number of different aircraft orientations and over a range of frequencies and transmitter characteristics (e.g., horizontally or vertically polarized). Measurements are taken at the FCS equipment to determine the level of current induced per unit of field strength. These results can then be compared with the results of the equipment bench tests. Testing will then progress to the powered aircraft configuration and a range of tests will be performed.

Typical tests are system interaction tests, onboard transmitter tests, and external transmitter tests. System interaction tests are performed to ensure that all aircraft systems are mutually compatible with each other, and in particular with the FCS. Thus, all modes of operation of each aircraft system must be selected and exercised during engine running tests to ensure freedom from cross system interactions. Where appropriate, measurements may be made of transients produced on the aircraft electrical bus bars as manually or automatically switched functions are operated. All onboard transmitters are exercised across their frequency range at normal and, where possible, at enhanced power levels to ensure freedom from EMI. Testing against external transmitters can also be performed in a number of ways. Traditionally, the aircraft under test has been exposed to each type of external transmitter likely to be encountered during its development and then ultimately its service life. Current test techniques utilize a test site with antennas capable of exposing the live aircraft to radiation over the appropriate range of frequencies (typically 2 to 1,000 MHz for RF and 1 to -8 GHz for microwave frequencies). Monitoring the behavior of the FCS during these tests can be done in a variety of ways. One option is to use the instrumentation system, but this requires careful interpretation since the instrumentation system on an aircraft can itself suffer from EMI. Instrumentation may be more likely to suffer from EMI because it is not necessarily designed to the same high levels of EMC hardness as the actual aircraft systems.

The generation of a clearance to fly in conditions of high-lightning risk is also very important in an aircraft development flight program and is essential for a service aircraft. Such a clearance requires a FCS that can survive lightning strikes. When digital computers were first used in FCSs, there were concerns that their processors could be corrupted by the electrical pulses generated by lightning strikes. System hardware and cable loom screening design processes have been developed to protect such equipment from lightning strike effects. These are particularly important on aircraft with composite structures. Although equipment bench tests can be used to demonstrate equipment resistance to lightning strikes and EMP, it is now often considered necessary to perform whole aircraft lightning strike tests to validate the design and clearance process. Such a series of tests requires a dedicated test facility including a test frame tailored to the particular type of aircraft under test. Although such testing is usually carried out with an unpowered aircraft, there are occasions where some testing is performed with a live FCS and it is important that the flight control engineer is familiar with such testing.

As the aircraft development program progresses, more EMC tests will be performed and it is important that all changes to both the FCS and the other aircraft systems are considered from an EMC point of view.

3.6 Flight Test Planning

3.6.1 General

Detailed test planning is one of the most important aspects of flight test preparation. This includes both ground and flight test plans. Poor planning results in a poorly conducted, inefficient, and unnecessarily risky flight test program. This section details the development of the flight test plan using knowledge and test data from the ground tests as a framework. This is not to imply that flight test planning cannot begin until the ground tests have been completed, in fact, initial flight test planning should begin well before many of the ground tests have been conducted. In general, test planning and particularly flight test planning, should be started early in the system design phase. Data from ground tests should be used to refine and update the flight test plans.

Preliminary flight test planning can occur as soon as the aircraft’s operational envelope is defined. The first requirement is a set of objectives for the development flight test program. For most new or modified systems this would include:

a. Verification of safe operation throughout the envelope,

b. Systems modification to ensure safe operation if necessary,

c. Verification, validation, and updating of systems models,

d. Validation of the systems capability to meet mission requirements, and

e. System modification to ensure capability to meet mission requirements.

These are the top-level, overall objectives that may often be broken down further into detailed objectives, which will define specific data, test, and analysis requirements. They all follow the basic philosophy of predict, verify, update, and validate. Although they are top level, they still provide sufficient information to design an initial flight test plan for the DFCS systems validation. The following will assume that the previously mentioned are the primary objectives, and describe the definition of an appropriate test plan to achieve the objectives for the DFCS. General test maneuvers can be defined that are appropriate to the maneuvering capability of the aircraft. As more complex models become available, and the system design starts to mature, refinements or updates can be made to the flight test plan. The earlier the flight test planning begins, the better thought out the test program will be.

Test plans are usually divided into regions for obtaining the objectives. The first is the verification of the safe operation within the intended operational envelope. The second is verification of safe recovery from areas, which may be outside the intended operational envelope, but may be entered as a result of maneuvering within the operational envelope. This would include such areas as departure and spin testing. The third area is the final validation of the systems mission suitability or effectiveness. The first two areas are usually considered envelope expansion, and the final area may be a portion of the envelope expansion or an entirely separate evaluation considered independently of the envelope expansion.

3.6.2 Data Requirements

The data and analysis requirements are specifically linked to the test objectives. The requirements must be designed so that they lead to the accomplishment of the objectives. Specifically, this means that the instrumentation, maneuvers, test conditions, and analyses are designed to provide information on stability and control, open loop flying qualities, handling qualities, model updating, and validation. In order to accomplish this, the DFCS test team must work in conjunction with the design engineers to define the specific information required. This will ensure that the test plan objectives are achievable. Test safety and efficiency must always be kept in mind when developing the test plan. Safety will dictate the order in which test points should be accomplished, generally building up from least to most critical. Test efficiency will dictate that the maximum information be extracted from each maneuver while at each test point.

The first consideration is obtaining data involving system stability and stability margins. These can often be obtained from classic maneuvers, which provide step, or sinusoidal inputs and swept sin wave frequency sweeps. Properly instrumented aircraft can provide data on the open-loop frequency response and stability margins, frequency and damping of the closed-loop system and frequency and damping of structural interactions. Closed-loop system damping can be determined from a simple input such as a doublet. Doublets should be small amplitude (within the bounds of linearity) and limited to a single cycle. They can be performed in each axis, pitch, roll, and yaw. Doublets not only provide data on basic closed FCS loop frequency and damping performance, but can also be used for aerodynamic parameter estimation (as discussed in a later section). The doublet is usually preferred over the step input since it tends to return the aircraft to the original conditions as opposed to a new condition defined by the step input.

Another maneuver, which takes longer than the doublet, but will provide more data, is the frequency sweep. This is a sin wave with varying amplitude and frequency with time. Data from the frequency sweep can be used in conjunction with a FFT analysis routine to derive the frequency response characteristics. The frequency response is only valid over the range of frequency input, but this is usually sufficient to adequately define the system. Closed FCS loop frequency and damping as well as open FCS loop characteristics can be derived, depending on instrumented parameters. These sweeps are also often accomplished in each axis. Both doublets and frequency sweeps may have to be repeated at varying magnitudes if investigating a highly nonlinear system. The variation in input magnitude will be dictated by the level of nonlinearity as well as test safety. Frequency sweeps can also be used for aerodynamic parameter estimation.

Pilot-out-of-the-loop flying qualities will be evaluated with the previously mentioned maneuvers as well as other maneuvers such as aileron rolls, rudder rolls, steady sideslips, and elevated g turns (wind-up turns [WUT]). The pilot-out-of-the-loop refers to the pilot inputting predefined, constant or slowly varying inputs and not actively reacting to or shaping the input for a desired response. Aileron rolls provide information on the aircraft’s lateral response characteristics, multiple axis coupling, maximum roll rate and roll mode time constant. Steady-heading or wings-level sideslips provide information on the basic static stability characteristics with sideslip. These are usually limited to the steady-state sidelsips achievable by the aircraft. Higher sideslip may be generated by rolls or other maneuvers. Slowly varying g turns or WUT provide information at elevated AOA. The WUTs will give information on apparent stability to the pilot and trim authority. Maneuvers such as rolls (both aileron and rudder) at elevated AOA will provide data on aircraft axis coupling, both inertial (gyroscopic) and kinematic (exchange of AOA and sideslip during a roll).

Handling qualities maneuvers will provide information on pilot-in-the-loop control of the system. The pilot is free to react to system response with inputs during pilot-in-the-loop maneuvers. In this sense, the pilot acts as an additional control system, and as such, can have similar performance and stability problems as any closed-loop system. These problems can be small and/or annoying but acceptable, or as bad as explosive PIO. The ability of the pilot to aggressively command the aircraft response will directly impact the ability of the system to perform the required mission. The mission will determine the amount of precise and aggressive control required by the pilot. Air-to-air combat will obviously require a higher level of aggressiveness and precision than cruising from one location to another. Handling qualities test maneuvers must be designed to adequately reflect the intended mission of the aircraft as well as to find any cliffs which may occur as the result of unexpected occurrences such as gust upsets.

Handling qualities are most often evaluated using specific representative mission maneuvers such as air to air tracking, formation flying, aerial refueling, and landing. These maneuvers are usually qualitatively evaluated via the Cooper-Harper rating scale (Reference 3). In order to apply the rating scale, specific tasks along with desirable and adequate performance must be defined. Figure 6 presents the Cooper-Harper rating scale. The scale is used by starting at the bottom and following the decision tree to achieve a rating. The Cooper-Harper scale is not a linear 1 to 10 scale rating system. To achieve valid data, the specific tasks and the desired and adequate performance must be specified and the decision tree followed for each evaluation. Simply performing an undefined task, without performance criteria, and supplying a 1 to 10 linear rating is not valid. The Cooper-Harper scale shown in Figure 6 is typically broken up into 3 Levels. Level I (1 to 3) specifies a satisfactory system. Deficiencies are usually considered acceptable. Level II (4 to 6) indicates a less than satisfactory, but often an acceptable system. The deficiencies may or may not require improvements to achieve the mission. Level III (6 to 9) indicates an inadequate system where the deficiencies usually require improvement. A Cooper-Harper rating of 10 has no level, as it is an uncontrollable system. It should be noted that the stability indicated may or may not be a system instability. The instability may be a result of a PIO as the pilot acts as a secondary FCS wrapped about the system.

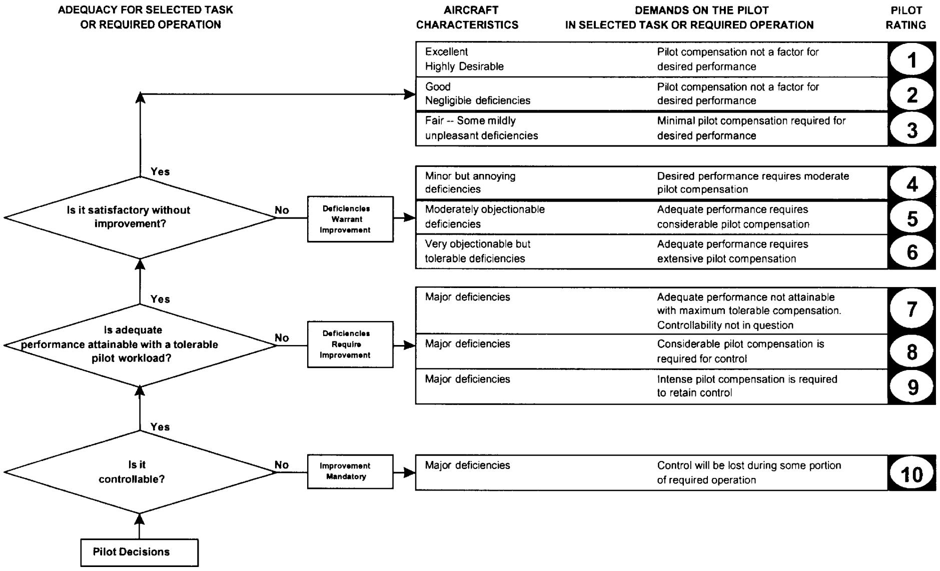
ADEQUACY FOR SELECTED TASK OR REQUIRED OPERATION
AIRCRAFT CHARACTERISTICS
DEMANDS ON THE PILOT IN SELECTED TASK OR REQUIRED OPERATION
PILOT RATING
Excellent Highly Desirable
Pilot compensation not a factor for desired performance
1
Good Negligible deficiencies
Pilot compensation not a factor for desired performance
2
Fair -- Some mildly unpleasant deficiencies
Minimal pilot compensation required for desired performance
3
Yes
Is it satisfactory without improvement?
No
Deficiencies Warrant Improvement
Minor but annoying deficiencies
Desired performance requires moderate pilot compensation
4
Moderately objectionable deficiencies
Adequate performance requires considerable pilot compensation
5
Very objectionable but tolerable deficiencies
Adequate performance requires extensive pilot compensation
6
Yes
Is adequate performance attainable with a tolerable pilot workload?
No
Deficiencies Require Improvement
Major deficiencies
Adequate performance not attainable with maximum tolerable compensation. Controllability not in question
7
Major deficiencies
Considerable pilot compensation is required for control
8
Major deficiencies
Intense pilot compensation is required to retain control
9
Yes
Is it controllable?
No
Improvement Mandatory
Major deficiencies
Control will be lost during some portion of required operation
10
Pilot Decisions

Figure 6 Ten Point Cooper-Harper Rating Scale

The PIO may or may not appear during the normal handling qualities evaluations. Many PIO occurrences are a result of some form of trigger not normally encountered during routine flight. The event may be something such as an emergency disconnect from the tanker, rapid maneuver to avoid collision, or sudden turbulence or gust. Pilot-in-the-loop oscillations encountered during these conditions are usually a high bandwidth pilot reaction to the abrupt aircraft response. Normal handling qualities testing may or may not evaluate the aircraft's PIO susceptibility under these conditions. Other piloted evaluations have been developed to try to separate these types of PIO tendencies from the normal operating envelope. Reference 2 describes the so-called HQDT technique developed at the AFFTC. The name is a misnomer, since the technique really evaluates PIO susceptibility, and is not a normal air-to air tracking technique as used in combat or the previously mentioned handling qualities evaluations. Handling qualities during tracking, as defined in Reference 2, is a specific high bandwidth, zero-error attempt to track a specified point on a maneuvering target. The pilot should aggressively zero out any error between the desired and actual aimpoint. This is done to achieve the highest possible pilot bandwidth in order to search for PIO tendencies. The technique as described in Reference 2 is not meant to replicate realistic pilot tracking techniques. The HQDT technique does not specify desired and adequate criteria; hence, use of the Cooper-Harper rating scale is not appropriate. Instead, a PIO rating scale, as shown in Figure 7, is used to categorize PIO susceptibly and impact. The HQDT technique has been involved in much controversy over the years, yet remains one of the few consistent tools available to test for PIO. Much of the controversy comes from the misnomer mentioned earlier. The technique is really a PIO evaluation technique, and not an evaluation of a mission representative maneuver.

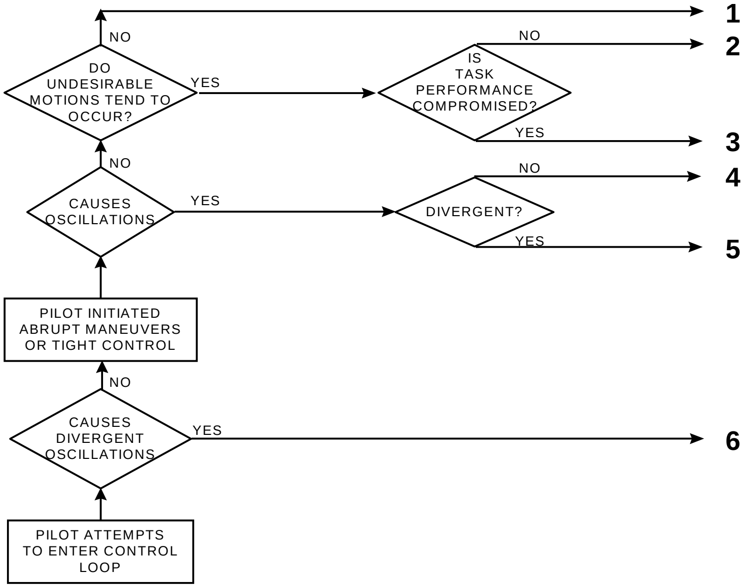
1
NO
2
DO UNDESIRABLE MOTIONS TEND TO OCCUR?
YES
IS TASK PERFORMANCE COMPROMISED?
YES
3
NO
NO
4
CAUSES OSCILLATIONS
YES
DIVERGENT?
YES
5
PILOT INITIATED ABRUPT MANEUVERS OR TIGHT CONTROL
NO
CAUSES DIVERGENT OSCILLATIONS
YES
6
PILOT ATTEMPTS TO ENTER CONTROL LOOP

Figure 7 Pilot-In-The-Loop Oscillation Rating Scale

3.6.3 Envelope Expansion

Envelope expansion test plans are laid out in a buildup fashion going from the region of lowest to highest uncertainty. The largest areas of uncertainty are in the rigid-body aerodynamics, the flexible aerodynamics and the unsteady aerodynamics associated with flutter and ASE. These uncertainties are highest at transonic Mach numbers, high AOA, sideslip, and dynamic pressures. The envelope expansion plan must therefore account for these uncertainties in the buildup process. This section will describe some techniques which can be employed. This is not the only technique which can be used, but it is illustrative of the thought process required for developing an envelope expansion test plan.

Once a set of given objectives have been defined, the next step in developing the envelope expansion plan is to obtain the expected operational envelope of the aircraft. Once the Mach number, or airspeed, altitude, AOA and load-factor limits are known, envelope regions can be developed for the expansion process. Basic flight test principles and maneuvers can then be used to start filling in the test conditions and maneuvers within these regions.

The DFCS flight test team must obtain the Mach, altitude, dynamic pressure, load factor and dynamic pressure envelopes of the aircraft as shown in Figure 8. Once these limits are known, then intermediate AOA and load-factor limits should be selected. The intermediate load factor limit is usually 80 percent of the design limit load (DLL). The intermediate AOA limit is usually 1.3 times the stall airspeed or in the case of fighter aircraft less than 15 to 25 degrees AOA. Expansion beyond these AOA and load factor limits usually requires specially equipped aircraft, and will occur later in the test program. The envelope should then be divided into regions as indicated in Figure 9. The regions are as follows:

Region 1	First or initial flights envelope
Region 2	Max altitude/Mach number expansion envelope
Region 3	Initial Limit AOA expansion envelope
Region 4	Maximum dynamic pressure expansion envelope
Region 5	Maximum lift or AOA envelope

Testing will normally progress in numerical order from Regions 1 to 2 to 3 and finally to Region 4; however, Region 3 is usually cleared in conjunction with Region 2 and as such, may be considered a subset of Region 2. Extended loads and the high AOA test programs will then be conducted to the final load factor and AOA limits within Regions 4 and 5. These will usually come after the initial envelope expansion and will be covered separately.

A first flight or first flights envelope (Region 1) should first be established. First flights are a unique case and the details will depend on whether the system is new or a modification of an existing system. The limits should be set within areas for which the uncertainty is low. Mach number, dynamic pressure, and AOA should be kept low. The initial envelope should be set at 10,000 to 20,000 feet, AOA and load factor as previously specified, and an airspeed or dynamic pressure limit below 0.7 Mach number and 200 to 350 KCAS. The dynamic pressure envelope may be defined in either incompressible dynamic pressure, equivalent airspeed or in terms of compressible impact pressure, and calibrated airspeed. Loads and structural engineers usually define limits in incompressible dynamic pressure or equivalent airspeed. The AOA limit for the first flights depends on the type of aircraft. Large transports or general aviation aircraft approach aerodynamic stall during the landing flair, and therefore, AOA up to initial stall may be set as the limit. For fighter-type aircraft where aerodynamic stall is well above approach and flair AOA, a limit of maximum flair AOA may be set.

The Region 2 envelope is usually defined on the right by the maximum dynamic pressure at the maximum Mach number and altitude combination and on the left by an AOA 15 to 20 percent lower than the initial limit. This limit should allow at least 2 to 3 gs maneuvering load factor capability at the lower airspeed bounds of the Region 2 envelope.

Region 3 is defined on the right by the AOA limit of Region 2 and on the left by the initial AOA limit. Region 3 is often cleared in conjunction with Region 2, and as such may be viewed more as a subset of Region 2.

The Region 4 envelope is bounded by the maximum Mach number and dynamic pressure on the right, and on the left by the initial dynamic pressure limit or the extent of the Region 1 expansion.

Region 5 is the maximum AOA expansion from the initial AOA limit. This is the portion of the envelope up to and above stall AOA. For fighter and trainer aircraft, this is where the departure, spin and other out-of-control situations are evaluated. This region often requires specially equipped aircraft to ensure safe recovery from out of control situations. Features such as stall or spin recovery parachutes, special backup power systems and instrumentation are often used for this region.

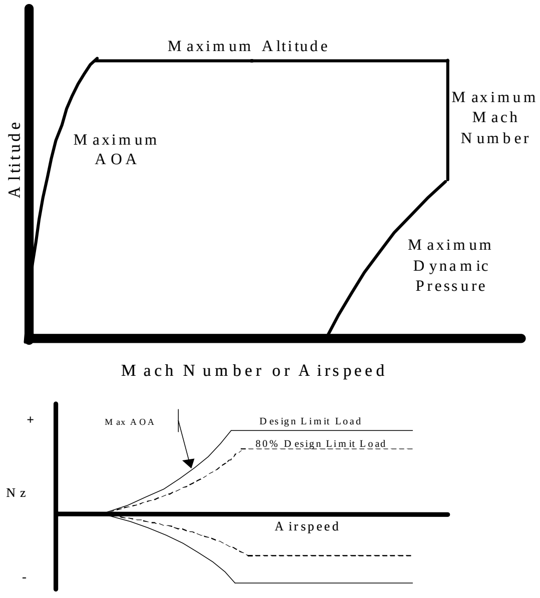

Figure 8 Basic Aircraft Envelopes

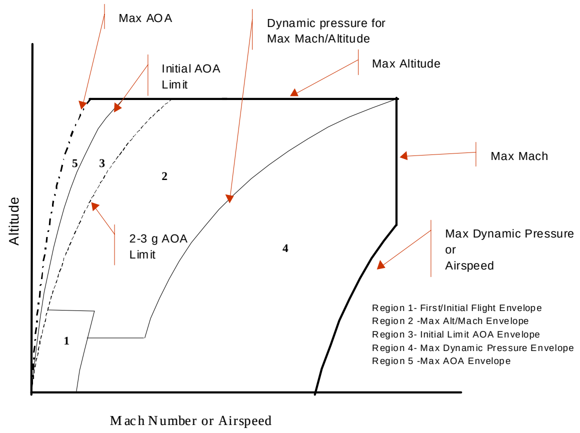
Max AOA
Dynamic pressure for
Max Mach/Altitude
Initial AOA
Limit
Max Altitude
Max Mach
5
3
2
Altitude
2-3 g AOA
Limit
4
Max Dynamic Pressure
or
Airspeed
Region 1- First/Initial Flight Envelope
Region 2 -Max Alt/Mach Envelope
Region 3- Initial Limit AOA Envelope
Region 4- Max Dynamic Pressure Envelope
Region 5 -Max AOA Envelope
1
Mach Number or Airspeed

Figure 9 Typical Envelope Expansion Regions

3.6.3.1 Envelope Expansion Maneuvers

Within each Region, the envelope is expanded in an orderly fashion, using a 3-step approach. Step 1 involves basic DFCS, flutter and ASE stability, aerodynamic parameter estimation maneuvers and mild maneuvering. Step 2 involves more aggressive maneuvering to specified limits and high gain handling qualities testing such as HQDT. Step 3 is a final operational handling qualities and mission effectiveness evaluation. Steps 1 and 2 are the primary safety oriented steps in the envelope expansion process. Step 3 may be done in conjunction with the other Steps or may be delayed until a safe envelope has been defined by Steps 1 and 2.

Figure 10 shows some of the typical maneuvers performed as well as information they provide during a DFCS envelope test process. Not all test programs will use every maneuver. Step 1 maneuvers test the basic FCS, ASE and flutter stability as well as collect data for system parameter identification and model updating. Step 1 also demonstrates mild maneuvering capability and elevated load-factor capability. Step 2 further expands the maneuvering capability to full inputs and load factor. Step 2 also tests for PIO susceptibility using zero error, high-bandwidth tracking (HQDT). Step 3 covers mission-related maneuvers and operationally-related handling qualities.

Step	Maneuvers	Purpose
1	1-g trims Control raps 3 axis doublets Frequency sweeps PTI for PID 1-g partial stick rolls 1-g partial rudder pedal rolls Partial pedal sideslips Wind-up turns (WUT) to elevated g	Basic trim capability, stability and control, aero-servo-elasticity, Parameter ID maneuvers, roll capability, roll coupling for small inputs, elevated g characteristics
2	1-g full pedal sideslips 1-g full stick rolls WUT to Nz /AOA limit Elevated g rolls, partial input Elevated g/AOA rolls, full input HQDT for PIO	Maximum maneuvering stability and control, maneuvering at max g/AOA, PIO susceptibility
3	1-g Cross control / coupled maneuvers Elevated g/AOA cross control/coupled maneuvers Operational handling qualities Air-to-Air tracking Air-to-ground tracking Aerial refueling Offset landings Systems unique HQ	Misapplied controls maneuvering, operational effectiveness

Figure 10 Typical Envelope Expansion Maneuvers

3.6.3.2 Order of Expansion for Region 1

The first flight, or set of flights, for any aircraft are always a unique occurrence. This applies not only to new aircraft, but also to those with modifications. By necessity they must all takeoff, conduct tests in some portion of the envelope and land. The landing is often considered one of the more dangerous portions of these flights, particularly with a new aircraft or new set of control laws. Handling qualities problems near the ground can be a dangerous situation. Many decisions must be made on the first flight of any new aircraft, which deal with not only the flight controls and flying qualities issues, but also with other systems operations. For first flights of modified aircraft, these issues of other systems operations may or may not come into play depending on the specific modifications.

The objectives of the first flight are to takeoff, obtain a limited amount of data to compare to predictions, and safely land. Because of the limited objectives, many programs prefer to leave the gear down on first flight to avoid potential complicating factors such as FCS mode transients or landing gear being stuck in the retracted position. Other programs may elect to retract the gear as part of the data required from first flight. Whichever course is taken, the first concern must be to ensure a safe landing capability. This means that tests to verify the flying qualities in the power-approach mode should be conducted as soon as possible after takeoff, and preferably before raising the gear for the first time.

Figure 11 shows an example first flight profile to verify the flying qualities in the power-approach mode prior to the first retraction of the landing gear. Takeoff and climb to the intended test altitude (gear down) is accomplished between the approach and gear-limit speeds. Test maneuvers are then performed at the speed and altitude indicated by point A in Figure 11. A deceleration to the approach speed is then accomplished and a similar set of maneuvers performed (point B in Figure 11). A further deceleration to an AOA 15 to 20 percent below approach speed should then be accomplished to ensure adequate stability and control for AOAs slightly above those at approach speed (point C in Figure 11). The maneuver set at point C will most likely be a subset of those performed at the previous points. An acceleration back to the original climbout speed is then accomplished and elevated load factor maneuvers are accomplished to the approach AOA and slightly above (point D in Figure 11).

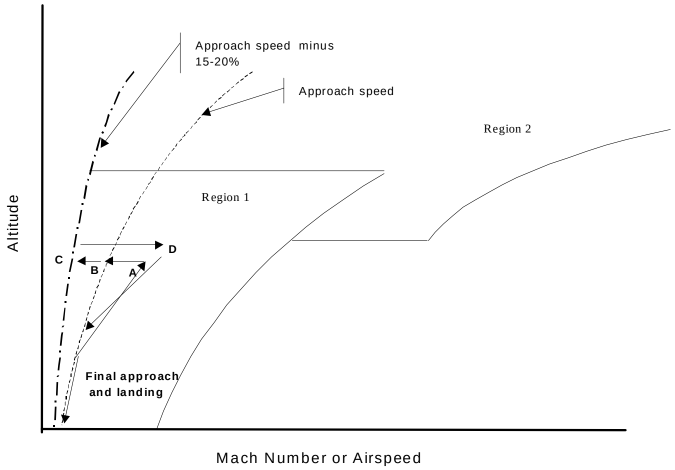

Figure 11 Typical First Flight Profile

Following these basic stability and mild maneuvering tests, high-gain handling qualities are evaluated with a zero error HQDT maneuver to evaluate PIO susceptibility. These should first be performed at the initial climbout speed and altitude, followed by the approach speed and an AOA slightly higher than approach speed. The high-gain tracking may be followed by practice landings at altitude. The final approach and landing can then be accomplished with the pilot having some knowledge of the general aircraft flying qualities capability before the actual landing. These maneuvers should be performed at the beginning of the first flight. As with any new system, one never knows when system problems may require an immediate abort of the flight. Accomplishing these as soon as possible maximizes the chance that they will be completed prior to the first landing. Most modern fighter-type or highly maneuverable aircraft have high aerodynamic stall AOA and most likely will not approach these AOAs during the landing flair. For this reason, full stalls on the first flights are not a good idea. However, transport and many training aircraft will approach aerodynamic stall on landing. With these aircraft, slow 1-g stall entries are often performed on the first flight to evaluate the stall characteristics.

Following the power approach flying qualities evaluation, the first flight can proceed to raising the gear and conducting further expansion as shown in Figure 12 (points E through H). This can either be done on subsequent flights or during the first flight. The goal is to get to a Mach number, airspeed and altitude from which to start the Region 2 expansion (Point H in Figure 12).

The initial altitude limit for Region 1 will depend on the type of aircraft being tested. In general, heavier and faster aircraft will have higher initial altitudes than slower lighter aircraft. For example, a military fighter or transport may pick an initial altitude between 15,000 to 20,000 feet, while a small general aviation aircraft may use an altitude as low as 5,000 feet.

3.6.3.3 Order of Expansion for Regions 2 and 3

The Region 2 expansion to maximum calibrated or equivalent airspeed can begin anytime after the first flight or after the gear are raised for the first time. The objective is to reach the maximum Mach number or airspeed at the maximum altitude. Once this has been achieved, then the Region 3 expansion can begin at the maximum altitude. Figure 13 shows a diagram of the expansion process for Regions 2 and 3.

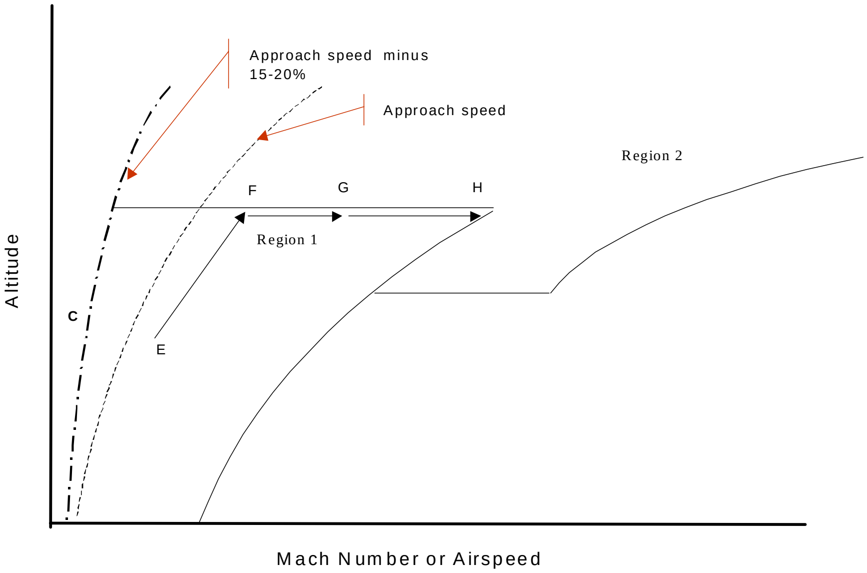

Figure 12 Further Expansion of Region 1

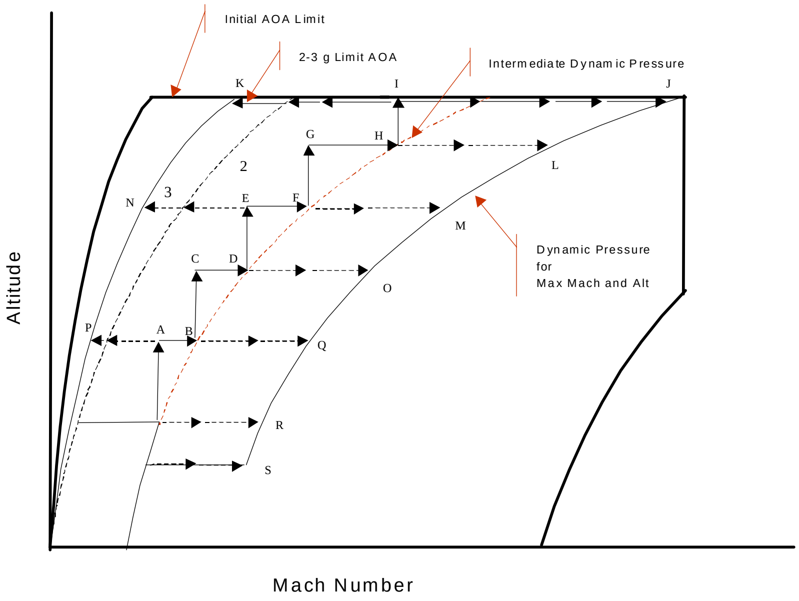

Figure 13 Typical Expansion Process for Regions 2 and 3

The first goal after raising the gear should be to expand to an anchor point (point H in Figure 12). A stair-step approach to reach the maximum Mach number and initial dynamic pressure limit is followed from point H, Figure 12, to point J, Figure 13. A constant airspeed climb is initiated at the anchor point altitude at an airspeed below that of the anchor point. A constant airspeed climb is desired, since this will tend to maintain AOA. This climb is maintained until an altitude where the initial Mach number of the anchor point is established. Once at this altitude, an expansion to the Mach number corresponding to the anchor point airspeed or dynamic pressure is conducted. New altitudes are selected to keep the Mach number with the constant climb airspeed below the maximum Mach number expanded to at the previous altitude. This process is repeated until the maximum altitude is reached. Once at the maximum altitude, expansion continues to the maximum Mach number and airspeed combination, point J, Figure 13. Once the maximum Mach number and altitude are cleared, expansion to the left into Region 3 can begin at the maximum altitude (points K, N, P Figure 13). Expansion to the dynamic pressure for maximum Mach number at lower altitudes (points L to S, Figure 13) can also proceed at this point. Maneuvers to the dynamic pressure for maximum Mach number and altitude combination and expansion into Region 3 can be carried out independent of each other; however, it may be more efficient to expand to both limits while at a given altitude.

Not all maneuvers at each Mach number and altitude combination need be completed prior to moving to the next combination. In fact, this is not necessarily the best approach. A similar stair step approach using the Step 1 and 2 maneuvers of Figure 10 can be employed. For example, it may be wise to clear the 1-g stability maneuvers from Step 1 at several Mach numbers ahead of the Step 2 maneuvers.

3.6.3.4 Order of Expansion for Region 4

Region 4 expansion to the maximum dynamic pressure usually begins after completion of the Region 2 and 3 expansion. The expansion is done by lowering the altitude and expanding in increments of Mach number or dynamic pressure as shown in Figure 14. The expansion can proceed either to the full maximum Mach number and dynamic pressure or in dynamic pressure increments. This will most likely be determined by structural dynamics considerations.

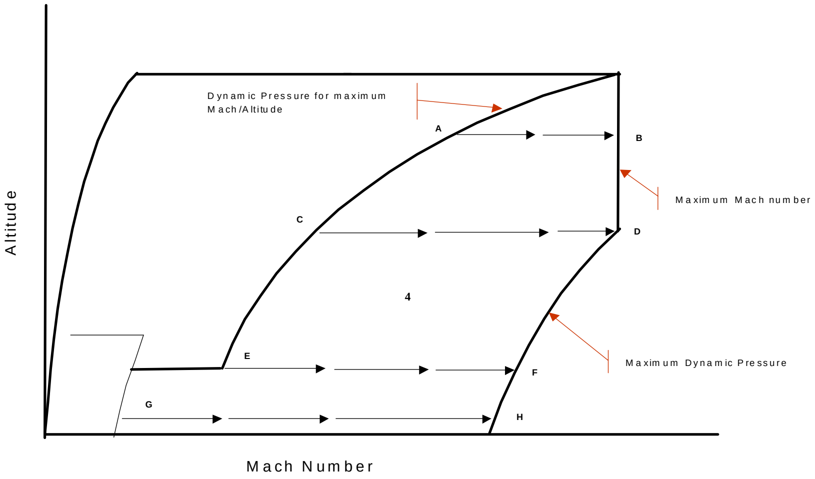

Figure 14 Typical Maximum Mach/Dynamic Pressure Expansion

3.6.3.5 Expansion for Region 5

The Region 5, or high AOA expansion is usually done last, although it may be done at the same time as other regions if multiple aircraft are used. Region 5 typically tests for stall, departure, and spin or deep stall, and recovery characteristics. Specially equipped aircraft are often required for expansion into Region 5. Special considerations such as recovery parachutes and emergency power sources are often required. These are most often used on military-type aircraft, although some general aviation programs also use these devices. The requirement to use such devices depends on the intended use of the operational aircraft and the potential for unrecoverable out-of-control modes. Military fighters often maneuver in a high AOA envelope, and may be susceptible to departure and possibly spins or deep stalls. Transport aircraft usually do not enter regions near stall intentionally and may not require extensive testing for spins or deep stalls.

The United States military has traditionally used MIL-F-83691B, *Military Specification Flight Test Demonstration Requirements for Departure Resistance and Post-Departure Characteristics of Piloted Airplanes* (Reference 4), for many years as a guide to testing in this region. The MIL-F-83691B spells out a detailed approach to testing departure, spin, or deep-stall susceptibility. There are generally four phases of such testing. Different phases are recommended for different classes of aircraft as defined by MIL-F-1797 (Reference 13) or MIL-F-8785. Phase A is straight ahead 1-g stalls and accelerated stalls, with recovery immediately after stall indication. Phase B is stalls with momentary aggravated inputs such as cross control or holding the stall. Phase C are the same inputs, except held for larger specified time periods. Phase D is usually attempted spins, deep stalls or other sustained poststall out of control maneuvers. The MIL-F-83691B also provides information on instrumentation and emergency device requirements.

Appropriate departure and spin and/or deep stall susceptibility should be investigated throughout the aircraft's operational envelope and configuration. This includes cg range and loading asymmetries. The use of simulation can be a great aid in helping reduce the unknowns in this region, providing that sufficient predictive wind tunnel work has been accomplished to lend credibility to predictions.

3.7 Safety Planning

3.7.1 General

Flight test safety planning is one of the most important tasks of any flight test team. Most flight test organizations have specific test safety planning guidelines for the DFCS test team to follow, as well as dedicated safety reviews prior to flight. The major benefit of the reviews is most often found in the preparation by the team for the review. The key to successful safety planning is involving the whole test team in the process; this includes both engineers and pilots. The safety planning process is in reality a risk management exercise. All flight test programs have inherent risk; it is physically and financially impossible to eliminate risk. The safety planning process attempts to strike a balance between reasonable risk minimization and test efficiency.

3.7.2 Hazard Identification and Minimization

A primary consideration for risk management is to start developing the safety plan early in the test planning process. As in test planning, much of the detail will yet to be preliminary, but the thought process should begin. Results from many of the tests, analyses and simulations previously defined in this document should be used in developing the safety plan. One of the more useful results will be from the failure modes and effects analysis and the failure modes and effects tests. Experienced flight test experts are also a valuable source for insight into potential test risks and should be consulted regularly during the safety plan development.

The basis for safety planning lies in defining both the ground and flight test unique hazards. The hazards should be unique to the test, and not general hazards which are always present when performing ground or flight operations. As an example, a bird strike hazard would normally be considered nontest unique unless there is something in the test plan that elevates the risk of bird strike above that occurring during normal flight operations. On the other hand, a loss of control hazard would be quite applicable during the high AOA envelope expansion of a new aircraft or FCS. The criticality of the hazard should also be defined in terms of a possible loss of aircraft or life, major aircraft damage or personal injury or minor aircraft damage with no injuries. Hazards also have causes; for example a loss of control hazard may be caused by a FCS failure or unpredicted aerodynamics. Potential causes for hazards should be identified where possible. This may come from the results of tests, analyses, simulations or previous flight test experience.

Once the test unique hazards and their causes have been defined, the test team should define techniques or procedures to minimize the occurrence of the hazard or its causes. Minimization procedures may include monitoring of critical systems, buildup procedures designed to spot a hazard prior to occurrence, additional tests or checkout procedures. The idea is to test in an intelligent fashion and avoid unnecessary risks. This is best accomplished by devoting considerable time and effort to thinking about what can go wrong. The objective is to perform risk management, not necessarily risk avoidance. In determining the hazards and minimizing procedures, the test team is really deciding what is the reasonable level of effort to minimize the chance of a hazard occurring. They try to strike a balance between reasonable expenditure of resources and acceptable risk. There is no single formula to apply to make this determination, each program and situation will be different, and must be addressed based on available data and experience.

The safety process should also define corrective actions to be implemented if one or more of the causes for a hazard should occur. There may be cases where no corrective actions are available to prevent the hazard from occurring; however, where applicable, they should be defined. The corrective actions may be checklist procedures such as actions for an engine flame-out, specific ground control and pilot actions or as simple as return to base or eject. The idea behind the corrective actions is to prevent the causes of hazards from proceeding to the full-blown hazard if possible. This again is a situation where risk management applies. Balancing the cost versus benefit of corrective actions, procedures or special equipment versus the safety benefit they supply must be well thought out.

3.7.3 Safety Reviews

The last part of the safety process is usually some form of an independent review of the test and safety planning. This review is usually conducted by knowledgeable and experienced individuals not directly connected to the test program. Their function is to take a broad and independent view of the program and review the entire planning process to ensure that the team has reasonably considered and minimized the potential hazards. The reviewers will not necessarily be experts in the specific test program, but should have experience in similar test programs. The review is really a final sanity check as to whether the team has done an adequate test and safety planning job.

3.8 Real-Time Monitoring

3.8.1 General

Real-time monitoring of the aircraft behavior usually is required by the specific safety considerations of the program. Even if the safety considerations do not dictate any need for real-time monitoring, benefits can be had through monitoring maneuvers for data quality. Real-time monitoring for smaller aircraft is usually done by telemetering the required data to a ground station for display. Some large transport aircraft have sufficient room onboard to provide the monitoring on the aircraft. Whichever method is used, the basics are similar.

3.8.2 Required Real-Time Parameters

Safety planning will usually identify the need for real-time monitoring as well as the required safety parameters to be monitored. The parameters should be divided into those required for safety-of-flight (SOF), safety-of-test (SOT) or mission critical (MC). The SOF means that monitoring of the parameter is required to safely fly the aircraft. These usually only occur with new or immature systems. The SOT are those monitoring requirements required for safely conducting a particular test, but are not required to normally fly the aircraft. The MC are those parameters, which are required for the test objectives to be met. If any SOF parameter is not working or available for monitoring, then the aircraft should not fly. If any SOT parameter is not working or available for monitoring then the specific test it is related to should not be performed. These parameters should be identified before flight and rigidly adhered to during a particular mission. The SOF or SOT parameters should be determined on the ground, prior to the mission, and should not be changed during the mission. Mission critical decisions are not considered safety parameters and can be changed during the mission. Since monitored SOF and SOT parameters may be critical to the test mission, and flight test instrumentation failures are common, the lists should be as short as possible. Only use the parameters absolutely required on the SOF or SOT list. This deserves careful attention as it is guaranteed that the situation will arise where a needed SOF or SOT parameter is not available. Failure to carefully scrutinize the real need for the parameters on these lists may result in the unnecessary loss of a test flight or maneuver due to poor planning. In addition, the list should be reviewed periodically to ensure that all parameters are still required as well as to ensure new parameters are added when needed. Another useful tactic to minimize the impact of parameter loss is to identify acceptable backup sources. Modern aircraft instrumentation systems often provide similar or the same data from a multitude of sources. Having the ability to switch to a pre-identified backup source will save time and money by minimizing mission loss.

3.8.3 Data Viewing Methods and Communications

Once the monitoring requirements are defined, the next step is to determine how they will be viewed. Monitored parameters may be required individually, or as a component of a computed parameter. Once the parameters and computations to be viewed are identified, then the means to view them should be determined. There may be many viewing options if modern control room equipment is used, or they may be limited by the capabilities of the control room. Modern control rooms offer both the classical stripchart viewing, as well as computer-generated displays for parameter viewing.

When the control room is used for SOF or SOT monitoring, careful attention must be paid to communication. The safety calls, and appropriate actions as a result of a call, must be determined prior to the mission, and are usually a part of the safety planning. All critical members of the control room crew must be conversant as to when to make calls, what the calls should be, and what the appropriate actions are. Since many safety calls may be time critical, communications with the aircraft must be considered. Most control-room procedures require a single interface, the test conductor, with the test aircraft. Calls are made to the test conductor by the monitoring personnel and then relayed to the aircraft. The intent is to avoid confusing and conflicting calls to the aircrew. Under some circumstances, the time criticality of a required safety action may dictate that the person responsible for monitoring the data must have rapid and direct access to the aircraft, by passing the test conductor. This practice is common for flutter testing, where critical actions must be taken as rapidly as possible to avoid severe safety problems. The team must carefully evaluate who can communicate with the aircraft and under what conditions it can be done. Multiple communicators between the control room and the aircraft must be kept to a minimum.

3.8.4 Team Philosophy

When a control room is added to a test program, the ground crew monitoring the system and the aircrew become an overall team. This team can be subject to the same crew coordination situations as if they were all in the aircraft. As with any in-flight crew duties, practice and training are crucial. This is especially true when the monitoring includes SOF or SOT duties where calls from the ground station to the pilot are required. The team should repeatedly practice and review the procedures. An excellent way of doing this is by using a ground-based simulation in conjunction with a control room. The simulation can then be used to practice and refine procedures. Another excellent practice is to confront the test team with unexpected failures or anomalies during the aircraft simulations. This is a practice perfected by NASA during the manned space program, and is also applicable to flight testing. Time spent by the team practicing with or without a simulator will greatly enhance the effectiveness and safety of any test program.

3.9 Simulation Usage

3.9.1 General

Real time, 6-DOF, piloted and batch (nonrealtime, nonpiloted) simulations are invaluable for preparing to execute a DFCS flight test program. The simulation can be used in all aspects of the previously mentioned subject areas in order to provide a thoroughly validated test plan and to provide general team training and preparation. The ability of the simulation to aid in the preparation for any flying qualities flight test program is limited only by the imagination of the test team and the fidelity of the simulation. Simulation use is irreplaceable in designing a safe and efficient test program. Simulation can be used to perform analyses of critical flight regions, maneuver design and sequencing, developing and practicing emergency procedures, developing minimizing procedures if hazards occur, and can also aid in estimating the schedule and cost for the test program. This section will outline some areas where simulation can be used to improve overall flight test preparation.

3.9.2 System Familiarization

Earlier sections of this document have stressed the need for a thorough and complete familiarization of the overall predicted system operations. One of the best ways to accomplish this is with simulation. Both nonreal-time and real-time piloted simulations are invaluable in familiarizing the engineer and pilots with the intended system operation. Engineers and pilots should use the simulations to provide an overall understanding of the predicted capability of the aircraft. Familiarization with the expected operational characteristics will be invaluable in planning, executing, and reporting for the flight test program.

One of the best practices that a DFCS flight test engineer can adopt is a regular schedule of personally flying a simulation. The engineer does not need to be a pilot or even terribly familiar with controlling an aircraft for this to be a valuable practice. Sufficient skills will be developed during regular simulation sessions to allow the engineer to adequately pilot the simulation. These sessions can be structured or simply free time to experiment. Having the engineer fly the simulation not only provides a better understanding of the expected flight characteristics of the aircraft, but it also helps foster a better understanding of the test pilots job and environment in which they have to work. This will improve communications between the team members during the test program. Significant engineer flying time may be restricted by the simulation schedule and cost of running the simulation; however, program managers should try to make time and budget available for the engineers to fly the simulator and should encourage the practice.

3.9.3 Flight Test and Safety Planning

Simulation use (piloted and nonpiloted) is indispensable in designing a safe and efficient test program. Simulation can be used to perform analyses of critical flight regions, maneuver design and sequencing, developing and practicing emergency procedures, developing minimizing procedures if hazards occur and also aid in estimating the schedule and cost for the test program.

With today's complex and integrated systems it is impossible to thoroughly test every aspect of a given system. By necessity, testing must be confined to the most critical and productive areas. Critical areas are those where predicted uncertainty is highest, regions of testing required to validate and/or update key models, high hazard regions, and regions of operational criticality. Key parameter variation studies can be conducted with the simulation in order to better define these regions. This information can then be used for the test plan design, allowing the test team to concentrate on testing the critical regions. Simulation will not be the only source for this type of information, but will be an additional tool in the process. For example, simulation is the best place to judge the sensitivity to variations in key aerodynamic parameters. When combined with the expected uncertainty from the wind-tunnel tests and past experience, regions of the flight envelope that require increased attention can be defined.

Piloted simulation is also invaluable in developing and practicing test maneuver definitions and sequencing. The maneuvers can be refined and practiced saving both test time and repeat maneuvers. Engineers as well as pilots should participate in this exercise. Engineers can provide feedback to the pilots on maneuver quality as well as add to their understanding of how the aircraft is predicted to operate. Pilots can use this feedback and their skills to develop the most efficient manner for gathering the required information. Hours spent in the piloted simulation practicing and developing the test maneuvers will translate to time and money saved during the test program.

3.9.4 Emergency Procedures

Simulation is also the ideal place to develop and practice emergency procedures. Both the classical flight manual procedures as well as emergency procedures for use during the test program can be developed and practiced on the simulation. For the test program, the latter is probably of the most benefit. This is particularly true when a real-time control room is in use during the program. Practicing the procedures, calls, and responses with the entire team in the loop will greatly enhance the ability of the team to handle unexpected anomalies and emergencies. The theory is the same as that for requiring the aircrew to routinely practice emergency procedures. In this case, the control room is as much a part of the aircrew as the pilots or other on-aircraft personnel.

In order to get the most benefit from emergency procedures simulation training, the piloted simulation must be connected to the control room or a reasonable replication of the control room. The former is the most beneficial, since it also allows the development and checkout of the control room displays as well as minimizing negative training on nonrepresentative equipment. However, even if the actual control room is not available, a reasonable facsimile is still extremely useful. The degree of fidelity required for the simulation control room is dependent on the emergency procedures and the displays in the actual control room. If the primary display in the control room consists of standard strip charts, than simply providing charts with similar layout and scales in the simulation may be sufficient. Computer generated displays in the control room may provide additional requirements for the simulation displays. The test team must make a judgment on what is the best overall solution to practicing emergency procedures using the simulation; however, they should not make the mistake of assuming that because the fidelity is not 100 percent, that the practice is not worth the effort. Even relatively simple rendition of the actual control room can have large beneficial impacts on team emergency procedure coordination.

Another necessary tool for practicing emergency procedures is to have the ability to insert failures into the simulation. The failures and their relative fidelity depend on the type of emergency procedures to be practiced. These failures should be inserted unexpectedly to surprise the test team and aid in developing proper crew coordination processes and procedures. It is almost guaranteed that initial procedures that have not been practiced will change as a result of this process. Reacting properly to emergency conditions and failures depends on constant and prolonged training. Proper training of the pilots and control room teams using the simulation will provide a significant increase in the safety and efficiency of the test program.

4.0 FLIGHT TEST EXECUTION

4.1 General

Flight test execution is where all the preparation and planning is finally put to its intended purpose. All the months and/or years of planning and preparation will now either pay off if they have been well done, or prove to be a hindrance if not. The test team should follow the test plan, but not be so inflexible as to ignore test results and be willing to modify the plan as necessary for both test safety and efficiency. The actual flight test execution phase should be well dictated by the preparation and planning, including a process to update the test plan as knowledge of the aircraft is gained. If the planning and preparation have been well accomplished, than the actual execution should be fairly smooth, even in the presence of surprises. This section will assume that the appropriate planning has been accomplished, and that the team is following the plan. The section will primarily cover additional subjects, which may arise when executing the test plan.

In general, the team should stick with the test plan; however, surprises can be expected. This will mean that portions of the test plan will need to be modified as test results become available. Modifications should be accomplished using an established process. Modifications can be in response to either better or worse than expected performance. Either case will require the modification of the original test plan.

Most DFCS flight test programs are an integrated effort covering technical areas outside of the stability, control, and DFCS arena. The aircraft envelope is normally being expanded for stability, control, handling qualities, loads, structural dynamics, propulsion, and systems operation simultaneously. This requires a disciplined process for coordination of all the requirements, concerns, aircraft or systems limits, and expansion sequencing for all of the technical areas of concern.

4.2 Test Plan Flexibility

4.2.1 General

No matter how well planned a DFCS flight test program is, a need to modify the original flight test plan will arise. The initial test plan is the result of the best information available at the time of its inception. The overall test planning process needs to be flexible and capable of reasonable modification over the life of the test program. As the aircraft’s capabilities are discovered during the test program, the initial test plan will require modification. Modifications can range from deleting test points to adding significant levels of test or retest. The test team needs to establish a consistent procedure for defining, approving, and validating test plan changes. Without an orderly and disciplined procedure, test plan modifications can adversely impact both test safety and efficiency. A well-planned process for test plan modification and updating needs to be in place prior to the beginning of the test conduct.

4.2.2 Major Test Plan Modifications

Major test plan modifications need to be conducted with all the care and analysis of the original plan. Modifications should be based on detailed analysis of the actual flight data and not hastily constructed between missions. Improper planning of major test plan changes can rapidly degenerate to at best a fly-fix-fly test program or at worst a disaster.

The reason for a test plan modification should be thoroughly understood by the test team. Test plan modifications should undergo the same rigor as used during the development of the original test plan. This includes using all of the knowledge and tools available to understand what the new objectives may be, and what impact the redesigned test plan will have on test safety and efficiency. Major changes should also be accompanied by a formal safety review as per the original test plan.

4.2.3 Minor Test Plan Changes

Not every change to the test plan calls for a major effort in exercising the modification process. Simple changes such as repeating test points, adding minor buildup maneuvers, and minor sequencing changes, can often be accomplished by the test team without major review. These changes should be restricted to those types which do not in any way change the intent or reduce the safety buildup content of the original plan. They should not consist of significant additional testing, which could impact the test cost and schedule. The limitations of allowable minor changes should be defined before the actual test conduct begins. Even minor changes to test planning should be coordinated throughout the test team to ensure that nothing which may impact other test disciplines is effected. These modifications need to be carried out prior to the mission prebriefing. Test plan changes should not be made during the mission prebrief.

4.2.4 Aircraft Operating Limits Process

The multiple engineering disciplines involved in a DFCS flight test program leads to the need for an integrated systems approach to the testing. Each discipline will likely have a separate set of operating limits and test completion requirements. These may well be conflicting and require coordination in both the planning and execution phases of the flight test program. In addition, the pressures from management or political sources may be to fly as many hours as possible. One way of ensuring that a disciplined coordination and analysis is done is through an expanding aircraft operating limit (AOL) process. The AOL process sets intermediate aircraft operating envelopes for each discipline as well as defining the analysis or demonstration required to clear for testing beyond the intermediate envelope. There should be a formal review and sign-off process for expanding the intermediate AOLs as the program progresses. The AOLs will expand as the aircraft is properly cleared through appropriate demonstration or analysis as defined by technical requirements and not outside political influences. The intermediate envelopes can often be established as subsets of the envelope expansion regions defined in Section 3. Each region can be segmented into smaller regions based on reasonable subdivision of Mach number, dynamic pressure, AOA or load factor. The AOLs should be divided into two categories. Category I is the total cleared envelope to date. This is the envelope where other testing can be accomplished without adhering to strict expansion procedures. Category II AOLs are a limited clearance to expand to broader envelopes while strict expansion procedures apply. This is actually a clearance to test beyond the limits of the current Category I AOL in order to proceed with envelope expansion. The Category II AOL should be upgraded to a Category I AOL when all of the prerequisite analysis and review has indicated that the aircraft is capable of safely operating within the new expanded region.

The AOLs should be reviewed by all disciplines involved in the flight testing. This will minimize the possibility of tests being conducted outside an appropriate AOL. A last check of the limits should be conducted by having all discipline leads review and approve the mission test cards. This should be accomplished prior to the actual mission prebriefing so that the briefing is accomplished with the final test cards. If significant anomalies are found during the mission prebriefing, the mission should be cancelled and a review of the mission test cards accomplished. No major test card modifications should be made during a final mission prebrief or during the mission itself.

4.2.5 Interrupting Test Progression

Perhaps one of the most difficult choices to be made during any flight test program is the decision to stop testing pending further analysis. This is especially true when the program has been proceeding smoothly to date, and then an anomaly is encountered. The decision to halt the expansion for further investigation should be made primarily on a technical basis; however, the decision to proceed should be made on both technical and a risk versus benefit (risk management) basis. The test team should not hesitate to halt the expansion if significant anomalies occur. If in doubt, stop and take a closer look at the test results. The decision to proceed should then be made after an analysis and review of the test results shows that it is prudent to proceed. Decisions to interrupt the progression of the program should be made from a conservative test safety point of view. If test safety is in doubt or unknown, than the assumption should be made that there is a safety issue, and the program halted until the issue can be resolved. It is better to assume a problem, take the proper time to review all of the issues and then make a decision, than to rush to judgment. An error in the first case results in lost schedule; the error in the latter could very well lead to a loss of aircraft or life.

The decision to proceed should be made on a risk versus benefit basis. The risk may well be higher than originally anticipated, but the information is sufficiently critical to justify proceeding. In this case, appropriate review of the original test and safety planning should be conducted to see if modifications are in order. Conversely, the risk may be higher than anticipated, and the information is not sufficiently critical to justify proceeding without extensive modifications to the test planning or the system design. Finally, the decision may be that there was no significant impact to test safety in spite of anomalous behavior, and that it is safe to proceed without system or major planning modifications. These decisions should be based on knowledge and preferably be made on the ground and not during the pressures of an ongoing test mission.

4.3 Mission Preparation

4.3.1 General

Just as important as the initial test planning and preparation is the individual preparation for each mission. The mission preparation stage is where all of the previous planning as well as integration of test results comes together. Proper mission preparation is required for a safe and efficient test program. Proper preparation for each mission must include: a review of previous tests accomplished and the results, a definition of the next set of desired points, and proper coordination between all technical disciplines involved in the test program. The test team must be disciplined and keep the goal of safe and efficient achievement of the test objectives in mind. There is often pressure to proceed with the test program as planned without carefully considering previous results. The test team must be capable of resisting this pressure when warranted, but must balance this with the need to efficiently conduct the test program. The team should not allow themselves to be pushed faster than they are comfortable with, but must also be able to realistically determine risk versus benefit.

4.3.2 Review of Past Tests

One of the difficult parts of any active flight test program is keeping up with the data analyses in order to determine if the test points flown to date supply adequate quality and quantity of data as well as to determine if the aircraft is performing as expected. It may seem that taking the proper time to analyze test results in lieu of more flying is standing in the way of a rapid test program, particularly if no large problems have been encountered to date. In fact, just the opposite is often true. Improper data analyses between flights can lead to increased problems and a slower and less safe program as time goes on. In addition, if the data quality and quantity were insufficient, then it may not be possible to meet the flight test objectives. Test points may be considered accomplished; however, if the data have not been reviewed, it is not known if sufficient data were acquired to meet the objectives.

The most obvious problem with insufficient analyses is being able to spot potential problem areas before they become a significant threat to test safety. Early highlighting of potential problems allows for revised test procedures or system modifications in order to maintain safety. This can be more efficient in the long run compared to waiting for a major problem to occur prior to redesigning the test program or system. In addition, even if the analysis does not adequately predict significant problems, the program is in a much-improved position to resolve those problems if critical data analyses have been conducted in parallel with the progress of the test program. Program delays may be minimized since a large portion of the required analyses have been completed. An example of this is the aerodynamic model updating process. If the analysts have kept a reasonable pace with the test program in updating the aerodynamic models, than designing the DFCS fixes or updates for mispredicted aerodynamics will happen much sooner than if the model updating must be completed prior to defining a fix.

Another critical reason for keeping up with the data analyses is to evaluate data quality. It does little good to find out after all of the flying is completed that a key parameter for obtaining a test objective was not working properly, or that the maneuver quality was insufficient. It is much more efficient to keep data analyses up to date as the test program proceeds in order to define any retest due to improper instrumentation or maneuver conduct.

Previously accomplished tests, and analysis results to date, must be reviewed as a part of any mission planning process. Failure to accomplish this can lead at best, to embarrassing situations where there was insufficient data to obtain the test objectives, and to the worst of allowing a dangerous situation to develop that may have been prevented. Neglecting data analyses solely to expand the mission accomplishment rate is neither an efficient or safe practice. This does not mean that the analysis requirements can not be redefined to increase the mission rate; however, this should only be done after a thorough review of the technical impacts of decreasing the analysis required between flights.

4.3.3 Test Cards

Flight test cards are the means by which the test team orders the sequencing of the testing and provides information critical to the conduct of the test. Card formatting and the information are critical to both the efficiency and safety of the flight test. There is no single format for test cards; however, all should present information in a straightforward, consistent, and logical manner. Many flight test organizations have detailed and specific instructions pertaining to card format and information to be included. This is an excellent practice and ensures some level of test card uniformity between test programs within the organization.

Test cards should contain information on the test condition, any specific configuration required, test maneuvers, and any key limits relative to the tests being conducted with that card. The first card or cards usually contain mission specific information such as test ranges to be used, mission frequencies, mission overview, and aircraft health. The test condition usually applies to the whole card (e.g., Mach number and altitude). The configuration would include such things as aircraft physical configuration, (e.g., gear flaps, loading, and cg), as well as information on any systems or subsystems configurations. The test maneuvers should be laid out in sequence of performance and indicate any requirements such as trim or retrim prior to maneuver execution. Any pertinent limits such as AOA, angle of sideslip (AOS), or load factor, for a given maneuver should also be indicated.

One of the most common mistakes in test card design is trying to overload the card with too much information. Too much information can clutter the presentation and make the cards difficult to read. The test pilot will be trying to read the test card as well as fly the aircraft. Cards with too much information or very small print will make this job more difficult and can impact test efficiency and safety. Test cards are also used by the test conductor and control room personnel to direct or monitor the progression of the testing. These individuals should have the same information as presented to the pilot, although the cards are often printed with more space for note taking.

4.3.4 Mission Prebrief

The mission prebrief is an essential part of any DFCS test program, a part that should never be skipped or minimized. The prebrief is not only a coordination meeting for the whole team to review the mission; it is also a last chance to catch any errors in the planned mission. The prebrief is where all of the pertinent information concerning the upcoming mission is presented, discussed, and reviewed by all involved. All aircrew and control room personnel involved in the mission should be at the prebrief. Briefed items should include: a mission overview, a review of any special mission assets required, an in-depth review and discussion of each test point and maneuver, a review of the pertinent test safety hazards for that mission, and a review of the applicable emergency procedures for that mission.

Major test plan or mission modifications should not be accomplished during the prebrief. Intended mission objectives and procedures should be coordinated prior to the prebrief. If major mission redefinition is called for as a result of the prebrief, the mission should be cancelled until the proper coordination has been accomplished. This does not mean that minor corrections of clarifications can not be made during the prebrief. The distinction between a major modification and a minor one is best judged by the experienced members of the test team.

4.4 Mission Conduct

4.4.1 General

Most of the DFCS test team’s participation during a test mission will be either on the ground in a control room or in-flight monitoring on a larger aircraft. Whether the mission is being controlled or monitored from a ground or in-flight control room, the entire team participating the monitoring becomes part of the aircrew.

As such, they have an obligation to conduct themselves and their jobs in the same professional and disciplined manner as a normal on-board aircrew.

4.4.2 Control Room Procedures and Protocol

The protocol in any control room (whether on ground or airborne) should be as strict as that for the test pilots. The test monitor's job is to continuously evaluate the aircraft or systems response for both data quality and safety implications. When either of these are compromised, they must then communicate the required actions to the test conductor and aircrew. This job requires knowledge of the parameters and system being monitored, concentration on what is happening to both the individual system and on the mission (situational awareness), and familiarity with actions and procedures to be used when the situation requires.

Because monitoring requires concentration and mission situational awareness, anything in the control room such as idle conversation, nonmission related reading, or anything else which is potentially distracting, must be strictly controlled. The basic rule should be that unless it is mission related, do not talk or visit; instead, the test team should continuously monitor their station for both safety and data quality. When mission-related communication is required, then it should be done in the defined and prescribed fashion, which was developed before the mission.

Each control room monitor is responsible for knowing their role and any specific actions or safety calls they are required to perform. They should be thoroughly familiar with all of their assigned duties. One method for reviewing and ensuring these capabilities is through some form of situational testing before the missions and/or during the mission prebriefing. On a recent AFFTC high AOA test program, this was accomplished during the prebrief (as well as with continual simulation practice). The test conductor would come to the brief prepared with specific emergency scenarios. The scenario would be described, than each member of the test team quizzed as to the appropriate actions or calls. This turned out to be an extremely beneficial and efficient method for ensuring that all kept up on their assigned duties in the control room and on the aircraft.

Visitors to the control room are undesirable, but unavoidable. If they are to be within the control room itself, they must be thoroughly briefed on acceptable behavior and not to interfere with the mission. It is preferable that if a test program is aware that there will be continual visitors to the control room, then separate facilities should be provided where visitors can not interfere with the conduct of the mission. Visitors should not be allowed to have any input into the mission itself while underway. Modifications by visitors to the planned test or emergency procedures should not be allowed. The test conductor or director should have the authority to have any visitor violating these basic rules removed from the control room, regardless of their rank or position.

Basic mission rules should be adhered to at all times and no modifications should be made while the flight is ongoing. Significant discrepancies or disagreements should result in mission termination and subsequent resolution on the ground. Arguments and unresolved action have no place in a flight test mission control scenario and must be avoided. It the responsibility of the test conductor (or director) to maintain control room procedure and decorum at all times.

4.5 Postmission

4.5.1 General

The events immediately following the mission can have as much impact on test efficiency and safety as those during planning and conduct. Proper mission debriefing and data analyses can significantly increase both test efficiency and safety. Poor postmission execution can and will adversely impact the overall test program.

4.5.2 Postflight Debriefing

The postflight debriefing is where all of the events during the mission are reviewed. Pilot mission conduct, planning, and control room comments are all appropriate subjects for the postflight debrief. The debrief should start with an overview of any significant mission events, followed by a detailed test card by test card review. Any anomalies in the aircraft operation should be discussed and reviewed. Unique actions to be performed (other than normal planned interflight activities) prior to the next mission should be defined. Any test points which require test based on mission results should be defined. Detailed pilot comments and handling qualities ratings are also reviewed and finalized at the postflight debrief. Pilot impressions on system performance are recorded.

Following the debrief, an initial mission report is usually prepared by the test conductor and pilot. This report summarizes the mission and critical information from the debrief. Test points accomplished, mission problems, system problems, and pilot comments are documented in the mission report. This report should be completed within 24 hours after the mission. These documents are absolutely necessary in order to record the progress and preliminary test results during the course of the test program. They will also become invaluable when preparing the final flight test program report, sometimes years after mission occurrence. Mission reports will be one of the primary data sources for the final report. Failure to maintain mission reporting within a reasonable timeframe of the mission occurrence will result in the loss of valuable test program information. As time goes by and other missions are accomplished, detailed information on any particular mission will be lost without these reports. The lack of a strict mission reporting policy or process is an indication of a poorly run test program, and one that may also have efficiency and safety problems.

4.5.3 Model Updating

The model updating process should proceed in parallel with the envelope expansion. Experience has shown that this is the best way to apply the predict, test, update, and validate test philosophy. The advantages of keeping the models updated are:

a. Understanding why the aircraft is operating as it is,

b. Having the best models available to analyze anomalies, and

c. Having the most knowledge possible about the aircraft from which to make informed decisions.

Keeping the models updated in parallel with the expansion requires dedicated manpower and significant planning. Many programs start out with every intention of applying this process, but rapidly revert to a fly-fix-fly operation. One of the main reasons for this occurring is improper planning early in the test program. Programs often underestimate the resources required to update the model. Early planning for resources, techniques, and tools are required in order for parallel model updating to succeed.

When the models are kept updated, the test team is in the best position to understand differences between predictions and actual system operation. The most efficient and safe way to make the necessary technical programmatic decisions is when those decisions are based on knowledge rather than supposition. One of the best ways to gain this knowledge is to use simulation combined with updated models. For DFCS and flying qualities test programs, the model that usually requires the most attention is the aerodynamic model. Fortunately, time demonstrated techniques are available for identifying key aerodynamic parameters from the test results. Similar techniques can sometimes be applied to the other models, but often are not. This may change, as simulation becomes a more integral part of flight testing in the future for a broad range of disciplines. The same philosophies used for updating the aerodynamic model would be applicable to other disciplines.

A dedicated team should be used to analyze the test data, develop the flight-derived parameters and update the models. This team’s sole responsibility should be updating the models from flight test results. The update team must be familiar with the form of the predicted models, potential uncertainty areas, planned update algorithmic forms and various parameter identification methodologies. The team leader should have prior experience in updating models based on flight test data. Updating models can be as much of an art as a science; therefore, the experience of the updating team will have a direct impact on the success and timelines of the effort.

The basic form of the most likely updates should be defined prior to the beginning of the flight portion of the test program. An excellent arena for accomplishing this would be during parameter variation studies. There will always be a need to modify the form of the updates as not all variations can be postulated. However, developing a basic mechanism within the model to accomplish these updates will greatly simplify the task during the test portion of the program. As an example, basic aerodynamic tables that add variations to the basic force and moment coefficients can be added to the model. These tables will usually be a function of the key aerodynamic independent variables such as Mach number, AOA, dynamic pressure, sideslip, and surface position. The tables are initially filled with zeros, and modified, as data become available. This method has been successfully used on several test programs.

4.6 Simulation Use

4.6.1 General

Use of simulation during the test execution phase is just as important as during the preparation and planning phase. The simulation can be used to provide detailed mission planning, emergency procedure training, predicted results, and aid in data analyses as well as anomaly resolution. The range of usefulness of simulation during the execution of the test program is only limited by the ingenuity of the test team. The use of simulation allows an understanding of how the system is supposed to operate, and why, as well as an understanding of how the system is actually operating and why. When system operation (both expected and actual) is well understood, then more informed decisions can be made relative to test execution.

4.6.2 Mission Training

Preflying missions or portions of a mission on the manned simulation can help to increase the efficiency and safety of the testing. Once the initial flight test mission cards are prepared, the intended execution sequence can be evaluated on the simulation. Test point or maneuver sequencing, not specifically ordered for safety or buildup, can be evaluated to ensure that the most efficient sequence is used to maximize the amount of data acquired for a given mission. In addition, the maneuvers can be practiced in order to gain proficiency in maneuver execution thereby reducing the amount of repeat points during the mission. The test team that will be monitoring the mission in the control room, should participate in the mission simulation sessions in order to gain knowledge on what the expected aircraft response is. This will allow the monitors to more readily assess the vehicle performance during the mission.

Continual emergency procedures training are also a valuable use of simulation during the test execution phase. This not only applies to the pilots, but also to the control room monitors. Unexpected failures or aircraft response should be incorporated into the simulation, and the pilot and/or control room responses exercised. This should be accomplished on some regular schedule in order to maintain team proficiency.

4.6.3 Data Analyses

The simulation can be an invaluable tool to aid in analyzing the test data. The analysis can be enhanced with a broad range of simulation capability, from nonreal-time batch simulations to full man-in-the-loop simulation. Comparisons can be made on a real-time or near real-time basis as the mission is progressing, as well as postflight. Most envelope expansion programs will use a reasonable combination of premission predictions combined with more detailed postflight comparison. Modern computer capacity has also allowed for the real-time or near-real-time comparison of simulation and flight results in the control room. The analysis can be even more productive if the models used (particularly the aerodynamic model) are kept updated from flight test results as the program progresses. Perhaps one of the most beneficial analyses is a direct comparison of the flight and simulation results. This can be a comparison of summarized data such as frequency and damping, and maximum rates, or more complex such as driving the simulation with flight measured inputs. The former is used when the test team does not have direct access to a simulation at the test site and must accumulate predicted data from planned off-site simulation sessions. The latter can give a direct time-history comparison between the predicted simulation response and the actual aircraft motion. Simulation and test data overplots are a more direct comparison method, but also more complex in that special implementation considerations (trim, integration drift, and nonstandard atmosphere) must be in place in order to drive the simulation with flight measured inputs. The time-history comparison is only as good as the models used in the simulation. Poor models, or incorrectly updated models can result in poor comparisons.

4.6.4 Anomaly Investigation

The simulation is also valuable in anomaly investigation. The same simulation types used for data analyses can also be used for anomaly investigation. In addition, subsets or simulations of particular portions of the system can also be driven with flight measured test data to isolate problems. Using the simulation to analyze flight anomalies allows for an understanding of the anomaly and as such, can lead to solutions. An example of this is available from the X-29 program. The X-29 DFCS control laws used a simplified model of the flaperon actuators for RM. The RM would declare the actuator failed when the model output exceeded the actual output by a predefined margin. A failure was declared by this monitor during the high AOA envelope expansion when a high frequency tail buffet entered the control laws via the roll rate feedback channel. The simplified actuator model used by the RM system could not accurately predict actuator motion imparted by the buffet, and hence a failure was declared. The real-time indication was of a failing servo, and the reason was not readily apparent. The cause of the declared failure was discovered by driving an offline simulation of the RM algorithm with the flight measured actuator commands. The failure of the simplified model to accurately predict the actuator motion was readily evident, and a redesigned model was developed and validated with the flight measured data. The redesigned model was then successfully tested on the aircraft.

5.0 DATA ANALYSES

5.1 General

As with most other aspects of developing a DFCS flight test program, early involvement in data processing is a must. The test objectives will drive the data requirements to satisfy the objectives. In turn, the needed results will define the data analyses techniques and instrumentation requirements. This section will cover some of the basic data analyses techniques often used in DFCS flight test analyses.

5.2 Data Errors and Corrections

5.2.1 General

Much of the raw data collected from the test aircraft will require corrections in order to evaluate the true value. The corrections are often a consequence of the environmental characteristics in which the sensors operate. The environmental factors can include such things as local aerodynamic flow, off cg measurements, structural vibrations, and instrumentation noise contamination. Consideration of the proper corrections must be included in any analysis. Failure to do so can often lead to erroneous and misleading analyses and evaluations.

5.2.2 Air Data

Airspeed and altitude are often measured from several sources during a flight test program. The aircraft may be equipped with a specialized nose or wingtip boom containing a separate Pitot-static source for determining airspeeds and pressure altitude. This boom may be in addition to a production system measuring similar data, but at a different location on the aircraft. Data from both must be corrected for position error, total pressure loss, and total temperature corrections. The nose or wingtip boom is often used during a test program since in theory it will have lower position error corrections due to placement of the Pitot and static sensors away from the aircraft flow field. Boom systems still require calibration in order to obtain the true values of airspeed, Mach number and pressure altitude. However, the smaller corrections (compared to a production system) provide data with less uncertainty than applying the same techniques to the production system. The corrected values from the boom data are then used to calibrate the production system. Most modern aircraft utilizing digital control systems will have an onboard air data computer (ADC) which will take the production measured values and apply appropriate corrections. Predicted corrections may or may not be available before first flight. The DFCS flight test team must be aware that any air data scheduled gains in the flight control system will be selected based on whatever the indicated output of the ADC is. This will not be the same as the true air data parameters until flight test generated corrections are obtained and implemented in the ADC. If no ADC or other correction source for the control laws is available, then the flight control system will be operating on different air data than the true values. This could impact the analysis of the flight data and also implies that the air-data parameters being used by the control laws should be an instrumented parameter.

Position error flight testing and error determination is a complex subject beyond the scope of this document. Reference 5 (*Standard Airspeed Calibration Procedures*) contains an excellent compilation of the classical position error determination techniques. Many of the older techniques, which are based on measuring speed and altitude relative to a known point, are being replaced with global positioning system (GPS) methodologies. For low altitude, subsonic position error methods the classic tower-fly-by or measured ground-course techniques are often used. For higher altitude and supersonic flight, pacer aircraft, inertial navigation system (INS), or radar methods can be used. Again, more modern techniques are beginning to use GPS as a reference measurement source for position error. Ground course, INS, and GPS methods give earth-referenced velocities, altitudes and positions. They do not directly account for winds or off standard day temperature profiles. Special flight test techniques and data analyses can be used to account for not considering the winds or off standard day temperature profiles. If neither are considered, the data can be grossly in error. The tower-fly-by and pacer aircraft methods avoid these problems and provide a more direct measurement of the errors than do the radar, GPS, INS, or ground course methods. However, these methods can also be more expensive and time consuming.

Understanding basic Pitot-static systems requires knowledge of the standard atmosphere models, the real atmosphere and how the Pitot-static systems work. Standard atmosphere models do not exist in reality, it is simply an average of measured atmospheric parameters over time. Chances are slim that any flight test program will ever be conducted where a standard day actually exists across the altitude envelope. One area often misunderstood is the relationship between true or tapeline altitude (the actual altitude above Mean Sea Level) and pressure altitude (the pressure for a given geopotential altitude on a standard day). A constant correlation is only available for standard day conditions, which almost never exist. Attempts to compare a direct tapeline measurement (such as with GPS) to a given pressure altitude are only valid for the test day pressure and temperature profiles with altitude. There can be differences ranging from tens to several thousand feet between pressure and tapeline altitudes with nonstandard day conditions. A comparison between the two cannot be made without knowledge of these profiles. Another area often misunderstood is the relationship between airspeeds and inertial speeds. Airspeeds are measured with respect to the local atmosphere and hence include winds. Inertial speeds are measured with respect to some fixed datum (typically the surface of the earth) and do not include winds. The difference between the two can be as large as several hundred knots, depending on the local atmospheric conditions.

5.2.3 Accelerometer Corrections for Off Cg Measurement

Accelerometers are almost never located at the aircraft cg. Corrections to the measured values must be applied to get the cg value of acceleration. The corrections can be large, depending on the location of the sensors and the level of aircraft maneuvering. Using the raw measured values as cg value without proper corrections can result in large errors. The following equations show the appropriate corrections to transfer the measured accelerations to the cg.

$$
\begin{aligned}
Nx_{cg} &= Nx_{measured} + \frac{l_x}{g}\left(q^2 + r^2\right) + \frac{l_y}{g}\left(\dot{r} - pq\right) - \frac{l_z}{g}\left(\dot{q} + pr\right) \\
Ny_{cg} &= Ny_{measured} + \frac{l_y}{g}\left(p^2 + r^2\right) + \frac{l_z}{g}\left(\dot{p} - rq\right) - \frac{lx}{g}\left(\dot{r} + pq\right) \\
Nz_{cg} &= Nz_{measured} - \frac{l_z}{g}\left(q^2 + p^2\right) - \frac{l_x}{g}\left(\dot{q} - pr\right) + \frac{ly}{g}\left(\dot{p} + qr\right)
\end{aligned}
\qquad (3)
$$

where:

$Nx_{cg} = CG\ value\ of\ x\ body\ axis\ load\ factor, g's$
$Ny_{cg} = CG\ value\ of\ y\ body\ axis\ load\ factor, g's$
$Nz_{cg} = CG\ value\ of\ -z\ body\ axis\ load\ factor, g's$
$Nx_{measured} = measured\ value\ of\ x\ body\ axis\ load\ factor, g's$
$Ny_{measured} = measured\ value\ of\ y\ body\ axis\ load\ factor, g's$
$Nz_{measured} = measured\ value\ of\ -z\ body\ axis\ load\ factor, g's$
$1_x,1_y,1_z$ = body axis location of accels relative to cg,
p,q,r = body axis angular rates, and
g = acceleration due to gravity.

The corrections are a function of the relative distance between the sensor and the aircraft cg (in body axis coordinates), the body axis angular rates and the body axis angular accelerations. Sensor location relative to the aircraft cg, measured accelerations, and body axis rates are common data from any flight test program. However, angular accelerometers are not common and often undesirable due to noise characteristics. The angular accelerations used in the above corrections are most often obtained by digitally differentiating the angular rates.

5.2.4 Vane Measured Angle-of-Attack and Sideslip Corrections

Vane measured AOA and sideslip has several error sources that must be accounted for. These errors are upwash, sidewash, structural flexibility, axis alignment, and rotational rate induced angles. Upwash and sidewash affect the AOA and sideslip vanes due to local flow about the aircraft. Structural flexibility arises from the fact that the aircraft will bend under varying flight conditions. Axis misalignment is a calibration and sideslip plane of measurement problem. The induced angles are a result of induced local velocities at the vane locations due to solid body rotation, which in turn result in angle measurement errors.

For noseboom mounted vane installations, upwash is primarily a function of the lift of the wing and location relative to the wing. Wingtip boom vane installations have a similar phenomena, but tend to have higher values of upwash, compared to a noseboom, due to their proximity to the wing vortex system. Wingtip boom AOA vanes can also have complex upwash characteristics due to the wingtip vortex. Forward fuselage mounted vanes have the influence of the wing's vortex system and are also heavily influenced by the local flow characteristics about the aircraft's nose. Upwash values typically range from 10 to 15 percent for a far forward located noseboom to as much as 30 to 40 percent for fuselage mounted vanes. Reference 5 gives classical flight test techniques for calibrating the AOA vanes for upwash. In addition, trajectory reconstruction techniques can also be used to estimate the upwash corrections.

Sidewash on a classical noseboom installation is often close to zero due to the lack of a significant lateral-directional flow field as strong as the lifting vortex in the longitudinal plane. Typical values for this type of installation may range from 0 to 10 percent. However, for nose or nose chin vane installations, sidewash can easily be as much as 50 percent and nonlinear with indicated sideslip. Sideslip measured from wingtip mounted installations can also be heavily influenced by the wingtip vortex. The literature is bereft of flight test techniques for calibration of a sideslip vane. Techniques similar to the classical calibration techniques for the AOA vane do not typically work due to the difference in physics between longitudinal and lateral directional flight mechanics. Typically, sidewash calibrations have been assumed to be zero. This is not a bad estimation for the classical noseboom installation, but as already indicated, can drastically be in error if using a chin or a wingtip mounted vane. However, the advent of modern trajectory reconstruction techniques has made the estimation of sidewash a tractable problem. The author has had excellent success in calibrating both noseboom and chin mounted sideslip vanes with trajectory reconstruction techniques.

In order to fully understand the induced angle corrections, the true definition of AOA and sideslip is necessary. The angles are defined in Figure 15. The AOA is the angle between the X body axis and the projection of the free stream true velocity vector upon the X-Z body plane. Sideslip is the angle between the free stream velocity vector and the X-Z body plane. Both are measured relative to the aircraft center of gravity. The true definition of sideslip is often misunderstood. Sideslip is often improperly defined as the angle between the free stream velocity vector and the X body axis. This is an incorrect definition and can cause large data analyses errors if improperly applied.

The vane-measured angles are not taken at the cg, which means that velocities due to body axis rotation will induce angles at the vane's location. The local velocities at the cg and at the vane location will be different as shown if Figure 16.

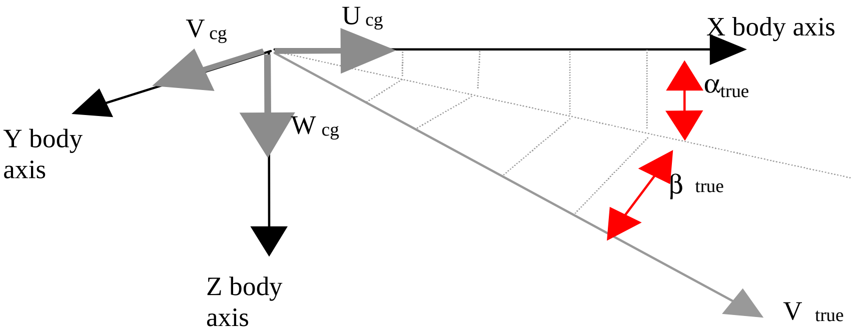

Figure 15 True Angle-of-Attack and Angle-of-Sideslip Definitions

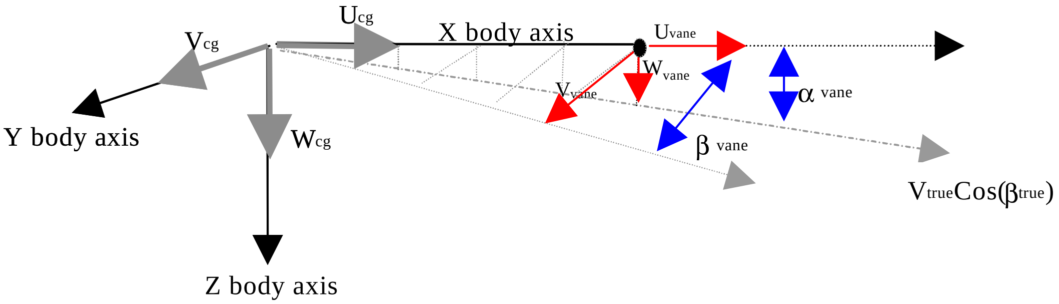

Figure 16 Vane Measured Angles

The angular rate corrections to vane measured angles can be derived as follows:

$$\begin{bmatrix} U_{vane} \\ V_{vane} \\ W_{vane} \end{bmatrix} = \begin{bmatrix} U_{cg} \\ V_{cg} \\ W_{cg} \end{bmatrix} + \vec{\Omega} \ X \ \vec{R} \tag{4}$$

where:

$\vec{\Omega}$ = $[p\ q\ r]^T$; body axis angular rates,
$\vec{R}$ = $[1_x\ 1_y\ 1_z]^T$; vane location relative to cg in body axis,
X = cross product operator,
U_{cg} = X body axis velocity at the cg,
U_{vane} = X body axis velocity at the cg,
V_{cg} = Y body axis velocity at the cg,
V_{vane} = Y body axis velocity at the cg,
W_{cg} = Z body axis velocity at the cg, and
W_{vane} = Z body axis velocity at the cg.

By definition;

$$Tan(\alpha_{vane}) = \left(\frac{W_{vane}}{U_{vane}} \right)$$
$$Tan(\beta_{vane}) = \left(\frac{V_{vane}}{U_{vane}} \right) \tag{5}$$

$$\begin{aligned} U_{cg} &= V_{true} COS(\beta_{true}) COS(\alpha_{true}) \\ V_{cg} &= V_{true} SIN(\beta_{true}) \\ W_{cg} &= V_{true} COS(\beta_{true}) SIN(\alpha_{true}) \end{aligned} \tag{6}$$

where:

α_{vane} = vane measured angel of attack,
α_{true} = true angle of attack,
β_{vane} = vane measured angle of sideslip, and
β_{true} = true angle of sideslip.

Applying the appropriate substitutions and algebraic manipulations, the following equations for true sideslip and AOA can be derived:

$$Sin\left(\beta_{true}\right) = \frac{1}{V_{true}} \left[Tan(\beta_{vane}) \left\{ V_{true} Cos\left(\beta_{true}\right) Cos\left(\alpha_{true}\right) + q l_Z - r l_y \right\} - r l_X + p l_Z \right]$$
$$Sin(\alpha_{true}) = \frac{1}{V_{true} Cos(\beta true)} \left[Tan(\alpha_{vane}) \left\{ V_{true} Cos\left(\beta_{true}\right) Cos\left(\alpha_{true}\right) + q l_Z - r l_y \right\} - p l_y + \right. \tag{7}$$

The equations are coupled between sideslip and AOA and also contain the true values of sideslip and AOA on both sides of the equation. Therefore, the equations must be solved iteratively using the measured vane values as starting points. Convergence is usually quite rapid. However, the corrections as formulated in equation 7 are only good for AOA and sideslips between ±45 degrees. Beyond these angles, the above formulation will diverge during the iteration.

There are some circumstances where the ±45-degree limitation can be avoided. If the AOA and sideslip vanes are located on a noseboom such that the X-body location of the vanes is much larger than the Y or Z-body locations, then it can be assumed that the only critical length is the X-body axis location. If this is the case, the following formulation can be used;

$$Sin\left(\beta_{true}\right) = \left[Tan(\beta_{vane}) Cos\left(\beta_{true}\right) Cos\left(\alpha_{true}\right) - \frac{r l_X}{V_{true}} \right]$$
$$Tan(\alpha_{true}) = \left[Tan(\alpha_{vane}) + \frac{q l_X}{V_{true} Cos(\beta_{true})} \right] \tag{8}$$

This new formulation does not suffer from the ±45-degree limitation; however, the new formulation must be used rather than simply setting the Y- and Z-body locations to zero in the previous formulation.

Another method has been postulated, which has the benefit of requiring no iterations. The author does not have any direct experience with this method and it is presented as a potential alternative to other methods. This method's validity in actual data analyses use cannot be validated by the author. Figure 17 shows the pertinent angles and relationships for this formulation.

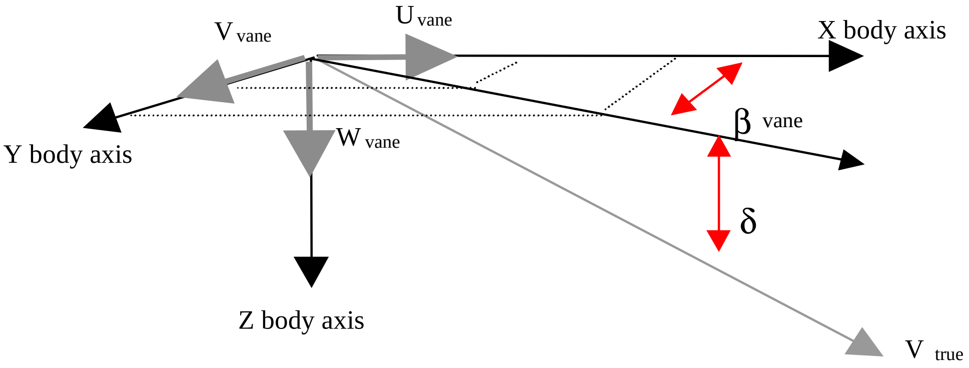

Figure 17 Simplified Correction Method

From Figure 17, it can be seen that;

$$\begin{aligned} U_{vane} &= V_{true}Cos(\delta)Cos(\beta_{vane}) = U_{cg} + (ql_z - rl_y) \\ V_{vane} &= V_{true}Cos(\delta)Sin(\beta_{vane}) = V_{cg} + (rlx - pl_z) \\ W_{vane} &= V_{true}Sin(\delta) = W_{cg} + (pl_y - ql_x) \end{aligned} \tag{9}$$

By definition;

$$\begin{gathered} Tan(\alpha_{vane}) = \frac{W_{vane}}{U_{vane}} = \frac{Sin(\delta)}{Cos(\delta)Cos(\beta_{vane})} = \frac{Tan(\delta)}{Cos(\beta_{vane})} \\ \delta = Tan^{-1}[Tan(\alpha_{vane})Cos(\beta_{vane})] \end{gathered} \tag{10}$$

The vane values and cg values of the body axis velocities are computed from:

$$\begin{aligned} U_{cg} &= U_{vane} - (ql_z - rl_y) \\ V_{cg} &= V_{vane} - (rl_x - pl_z) \\ W_{cg} &= W_{vane} - (pl_y - ql_x) \end{aligned} \tag{11}$$

Angle of attack and sideslip are then computed from the definitions of these angles.

$$\begin{aligned} V_{true} &= \sqrt{U_{cg}{}^2 + V_{cg}{}^2 + W_{cg}{}^2} \\ \alpha_{true} &= Tan^{-1}\left(\frac{W_{cg}}{U_{cg}}\right) \\ \beta_{true} &= Sin^{-1}\left(\frac{V_{cg}}{V_{true}}\right) \end{aligned} \tag{12}$$

In all the pervious formulations there is an inherent sideslip correction when the body axis rates are zero. In the absence of body axis rates or upwash and sidewash, the above reduce to:

$$Tan\left(\beta_{true}\right) = Tan(\beta_{vane})Cos\left(\alpha_{true}\right) \tag{13}$$

$$\alpha_{true} = \alpha_{vane}$$

In this special case, vane measured sideslip must be corrected for true AOA. This results from the fact that most sideslip vanes measure the sideslip in a fixed plane (typically the X-Z body axis plane). This is contrary to the definition of sideslip as shown in Figure 14. The fixed plane measured sideslip is often referred to as flank sidelip in much of the literature, and is not the same as the definition of true sideslip given earlier.

5.2.5 Inertial Navigation System Corrections

Modern flight test techniques often use the INS for computing various air data parameters including airspeed, dynamic pressure, AOA and sideslip. The computations for these are outlined in a later section. However, the INS data also require some corrections prior to applying these techniques. The INS typically supplies the North, East and Down (NED) velocities as well as the Euler Angles and body-axis rates. Since the Inertial Measurement Unit (IMU) is typically not located at the center of gravity, solid body rotation will induce velocities that are not experienced at the cg. The equations for correcting the INS velocities back to the cg are:

$$\vec{V}_{cg} = \vec{V}_{INS} - \vec{\Omega} \;\; X \;\; \vec{R} \tag{14}$$

where:

$\vec{\mathrm{V}}_{\mathrm{cg}}$ = Body axis velocity vector at cg,
$\vec{\mathrm{V}}_{\mathrm{INS}}$ = INS measured velocity vector,
$\vec{\Omega}$ = Body axis rate vector,
$\vec{\mathrm{R}}$ = Location vector of INS wrt cg, and
X = Cross product operator.

Acceleration corrections to the INS/IMU data may also be required; these are similar to those for accelerometers discussed previously.

Corrections to IMU/INS measured angles and accelerations may be required due to fuselage bending. These are usually difficult to estimate and generally apply only to steady-state conditions such as constant load factor maneuvers. For most flying qualities applications, corrections due to fuselage bending are ignored.

5.3 Other Analysis

5.3.1 General

Many other types of analyses are typically performed on the DFCS flight test data. This section will briefly cover some of the typical analyses and data preparation required to perform the analyses.

5.3.2 Aliasing

Aliasing during the digitization of an analog signal was covered in Section 3 during the discussion on instrumentation. However, aliasing can occur whenever any signal, whether digital or analog, is sampled at a rate insufficient to define the highest frequency in the signal. Aliasing can also occur when re-sampling a digital signal at a lower rate than the original signal was sampled. This is typical for many analysis applications; the sample rate of the basic data may be much higher than that needed for the analysis and the data are often re-sampled at a lower rate. This can lead to aliasing in the lower rate data. To properly re-sample, the data must be re-filtered with a digital filter at the full rate and then re-sampled at the lower rate.

Figures 18a and b illustrates what can occur when a signal is sampled at a rate below that prescribed by Nyquist theory. Figure 18c shows the same signal sampled at the Nyquist frequency. Figure 19 illustrates how aliasing of noisy data can induce low frequency oscillations in the sampled data that do not exist in the analog signal.

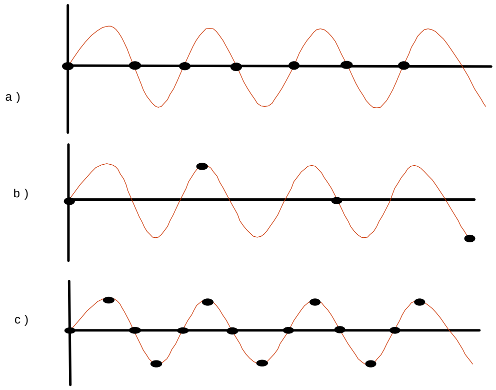

Figure 18 Nyquist Sampling Theory

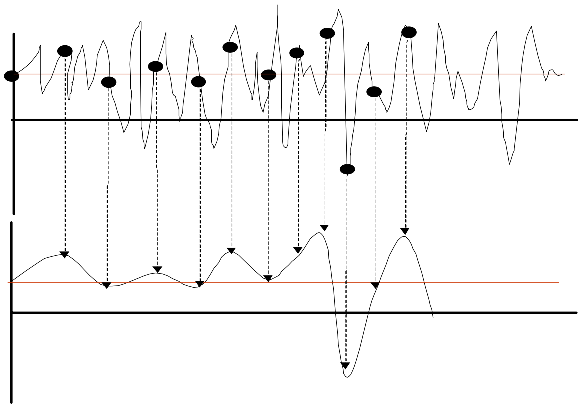

Figure 19 Aliasing of High Frequency Data to a Lower Frequency

5.3.3 Parameter Differentiation and Integration

Differentiation and integration of measured flight test signals plays an important part in the flying qualities and digital FCS analyses. Differentiation is critical in obtaining parameters for correction of accelerometers as well as determining the aerodynamic moments being applied to the aircraft. Integration is important in simulation, trajectory reconstruction and in validating any differentiation algorithm. Reference 6 (*Digital Filters*) gives a good overview and technical discussion on signal differentiation and other filtering aspects. Reference 7 (*Aircraft Control and Simulation*) gives a good discussion on digital integration routines used for simulation. This section will review some key characteristics and describe some typical methods used for differentiation and integration.

The simplest digital differentiation scheme is a direct difference equation, where the difference between the dependent variable at each sample time is divided by the difference in the independent variable:

$$\frac{dy}{dx} \approx \frac{y(n+1) - y(n)}{x(n+1) - x(n)} \tag{15}$$

where:

x = independent parameter and
y = dependent parameter.

By definition, this is the estimated derivative at the one-half sample period between points. Applying the derivative at one of the sampled points will introduce a one-half sample time shift. This can be accounted for by performing the computation and then interpolating the derivative back to the sample times, or by averaging with the previous computation to obtain the derivative at the point of interest. The difference in Equation 15 is the most direct computation, but also has the disadvantage of supplying the most noise amplification. The noise can be attenuated by applying any of several filtering algorithms explained later in this section. Reference 6 also includes schemes for applying the differentiation and filtering process in a single step.

Another method used for differentiation is to fit a second (or higher) order polynomial though N data points distributed before and after the time point in question. The derivative at the time point in question is then readily computed by applying the analytical derivative of the polynomial at that point. The number of points used will also act as a smoothing device, the smoothing effect increasing with the number of points. Equation 16 shows an example for a second order polynomial:

$$y(t) = ax(t)^2 + bx(t) + c \tag{16}$$

In Equation 17, a, b and c are solved via a least-squares fit of the data points passing through the I’th data point of interest. Once the coefficients have been estimated, then the derivative at the I’th point is computed by:

$$\frac{dy_i}{dt} = 2ax_i + b \tag{17}$$

Integration is also used extensively in follow-on data processing involving simulation or trajectory reconstruction. Reference 7 covers several excellent digital integration schemes for data processing or simulation use. Integration of a digital signal also suffers from the discrete nature of the data. Inaccuracies in the integration process arise from assuming the integrated signal is held constant over the time interval of interest, adding error. The error typically will be reduced as the sampling time decreases. The author has had excellent luck in using either third or fourth order Runnga-Kutta fixed interval routine, which is a good compromise between computational speed and integration error.

5.3.4 Mass Properties

The mass properties of an aircraft include the total gross weight, three axis cg locations, and the moments and products of inertia. Gross weight, cg location and inertias are constantly changing on an aircraft due to stores carriage or separation as well as fuel burn. The degree of these changes over a test mission will depend on the aircraft and particular mission.

Mass property computation is extremely important for flying qualities and DFCS data analyses. The dynamics of the aircraft can vary significantly with changes in weight, cg and inertia. Unfortunately, accurate mass property information can be difficult to obtain for a dynamic maneuvering aircraft. The main problem is accurately measuring fuel quantity and location during maneuvering flight. Even with baffled tanks, fuel is constantly moving during dynamic maneuvers and determining the local cg of the fuel is almost impossible. In addition, fuel slosh can invalidate the quantity measurements of the fuel probes. Accurate mass properties computations require both accurate quantity and location information, neither of which exist during many flight test maneuvers. A solution to this problem is to compute the mass properties during benign trim maneuvers, prior to a maneuver entry, and then hold the values constant during the maneuver. Most flying qualities-type maneuvers are of short enough duration that the fuel burn is inconsequential during the maneuver. Another solution is to compute the mass properties at a benign trim point before and after the maneuver and linearly interpolate with time. However, neither solution will provide accurate mass properties computations during the dynamic portion of the maneuver. Fortunately, the approximations mentioned should provide sufficient quality data for further analyses.

The static 3 axis centers of gravity about a fixed datum can be computed using the following equations:

$$X_{cg\ d} = \frac{W_{t0} X_{cg0} + \sum_i W_{ti} X_{cg\,i}}{W_{t0} + \sum_i W_{ti}} \tag{18}$$

$$Y_{cg\ d} = \frac{W_{t0} Y_{cg0} + \sum_i W_{ti} Y_{cg\,i}}{W_{t0} + \sum_i W_{ti}}$$

$$Z_{cg\ d} = \frac{W_{t0} Z_{cg0} + \sum_i W_{ti} Z_{cg\,i}}{W_{t0} + \sum_i W_{ti}}$$

where:

W_{t0} = basic zero fuel weight,
X_{cgd} = Xcg from measurement datum,
Y_{cgd} = Ycg from measurement datum,
Z_{cgd} = Zcg from measurement datum,
X_{cg0} = basic zero fuel Xcg from measurement datum,
Y_{cg0} = basic zero fuel Ycg from measurement datum,
Z_{cg0} = basic zero fuel Zcg from measurement datum,
W_{ti} = individual fuel or stores weight,
X_{cgi} = individual fuel or stores Xcg from measurement datum,
Y_{cgi} = individual fuel or stores Ycg from measurement datum, and
Z_{cgi} = individual fuel or stores Zcg from measurement datum.

The moments and products of inertias about a fixed datum can be calculated as follows:

$$\begin{aligned}
I_{xx\,d} &= I_{xx0} + \sum_i m_i \left(l_{y_i}{}^2 + l_{zi}{}^2 \right) + \sum_i I_{xxi} \\
I_{yy\,d} &= I_{yy0} + \sum_i m_i \left(l_{xi}{}^2 + l_{zi}{}^2 \right) + \sum_i I_{yyi} \\
I_{zz\,d} &= I_{zz0} + \sum_i m_i \left(l_{y_i}{}^2 + l_{xi}{}^2 \right) + \sum_i I_{zzi} \\
I_{ab\,d} &= I_{ab0} + \sum_i m_i \left(l_{ai}\ l_{bi} \right) + \sum_i I_{abi}
\end{aligned} \tag{19}$$

where:

I_{xxd},I_{yyd},I_{zzd} = moments of inertia about measurement datum,
I_{abd} = cross products of inertia about measurement datum,
I_{abi} = cross products of inertia about own cg,
$I_{xxi,}I_{yyi,}I_{zzi,}I_{abi}$ = i'th component inertias about own cg,
$I_{xxo,}I_{yyo,}I_{zzo,}I_{ab0}$ = baseline aircraft inertias about aircraft zero fuel cg,
m_i = individual fuel or stores mass,
$l_{xi,}l_{yi,}l_{zi}$ = distance of individual fuel/store from measurement datum, and
i = index of individual fuel or store.

The inertias must now be transferred from the fixed datum to the aircraft cg;

$$
\begin{aligned}
I_{xx\ cg} &= I_{xx\,d} - \frac{Wt}{g}\left(Y_{cg\,d}^{\;2} + Z_{cg\,d}^{\;2}\right) \\
I_{yy\ cg} &= I_{yy\,d} - \frac{Wt}{g}\left(X_{cg\,d}^{\;2} + Z_{cg\,d}^{\;2}\right) \\
I_{zz\ cg} &= I_{zz\,d} - \frac{Wt}{g}\left(Y_{cg\,d}^{\;2} + X_{cg\,d}^{\;2}\right) \\
I_{ab\ cg} &= I_{ab\,d} - \frac{Wt}{g}\left(a_{cg\,d} b_{cg\,d}\right)
\end{aligned}
\tag{20}
$$

where:

$I_{xx_{cg}}$, $I_{yy\ cg}$, $I_{zz\ cg}$, $I_{ab\ cg}$ = aircraft inertias about aircraft cg,
a_{cgd}, b_{cgd} = appropriate component cg locations,
W_t = total aircraft weight, and
g = acceleration due to gravity.

Problems can be encountered when accounting for fuel inertias about its own cg. Since liquid fuel does not act exactly as a rigid body, simply computing the mass moment of inertia about the fuels cg may cause error. Assuming the fuel to be a rigid body is an assumption whose validity depends on factors such as, the amount of fuel in the tank, the shape of the tank, the amount of baffling in the tank, and the location of the tank with respect to the center of rotation. This is a problem which has no direct or simple solution, only varying degrees of approximation. One solution is to assume the fuel acts as a rigid body and use its static inertia about its own cg. If the fuel tank is located a significant distance from the aircraft cg such that the mass contribution to the aircraft's inertia is much larger than the fuels own inertia contribution, than it may be possible to ignore the fuels inertia about its own cg. Another method is to combine the two methods, and assume that the fuel will act somewhere between having rigid body inertia and no inertia about its own cg.

5.3.5 Parameter Filtering

Reference 6 contains algorithms for filtering and smoothing digital signals. The subject can be complicated, and care should be taken to properly apply any filtering technique. Filtering inherently adds phase lag to any signal processed through the filter. However, if the full-time history of a digitized signal is available, the phase lag can be accounted for. Simply reversing the time sequence of the signal and reprocessing back through the filter and then reversing the time sequence back to the original will remove the phase shifts imparted by the filter. This will also provide a doubling of the gain attenuation characteristics of the filter. This method will only work if the entire time sequence of the signal is available, it will not work for a real-time application. Real-time filters will inherently add phase lag to the signal.

Phase lags imparted by filtering can be critical when trying to apply some postflight processing techniques such as parameter identification, trajectory reconstruction, or comparison to simulations. For these applications, the relative phase lag between signals can be critical. The relative phase lags can be eliminated by either applying the above forwards/backwards scheme to recorded data, or by applying the same filter to all signals to be analyzed. The latter will work in a real-time environment.

A multiple pole Butterworth filter and a forwards/backwards filtering algorithm is often used to postflight filter flight test data. Filter parameters are determined by the sampling rate and power spectral density (PSD) characteristics of the unfiltered signal. Sufficient data from a variety of maneuvers are analyzed to determine the best compromise for the filter parameters. When differentiation is involved, the parameters are further checked by reintegrating the differentiated signal and comparing with the original.

5.3.6 INS Air Data Computations

Air data can be computed from the three axis IMU velocities such as those from a modern INS. However, an IMU/INS only generates velocities relative to the earth, and does not account for the winds. Air data are measured relative to the local air mass and do include the winds. The IMU/INS measured velocities must be corrected for winds in order for them to be used for air data computations. The primary challenge with using the INS/IMU velocities becomes one of computing the local winds. Atmospheric balloon measured winds are usually not acceptable since they are inaccurate (to the degree required) and the winds can vary significantly from the time of the balloon measurement to the time of the test. The computation of the winds can be achieved in many ways, depending on the desired application. All methods require separate and accurate measurements of airspeed, pitch attitude, bank angle and heading angle. In most methods, assumptions must also be made which can impact the accuracy of the results. The following will describe several methods for obtaining the winds.

Equations 21 through 24 describes the general method for computing the winds. True airspeed (V_{true}) is measured from a separate source such as the calibrated Pitot-static system. The winds are required in the NED axis system as opposed to the wind-axis system where the true airspeed is measured.

The transformation matrices from the wind-axis system to NED system are:

$$[\psi]=\begin{bmatrix}\cos\psi & \sin\psi & 0\\ -\sin\psi & \cos\psi & 0\\ 0 & 0 & 1\end{bmatrix}\quad[\theta]=\begin{bmatrix}\cos\theta & 0 & -\sin\theta\\ 0 & 1 & 0\\ \sin\theta & 0 & \cos\theta\end{bmatrix}\quad[\phi]=\begin{bmatrix}1 & 0 & 0\\ 0 & \cos\phi & \sin\phi\\ 0 & -\sin\phi & \cos\phi\end{bmatrix} \tag{21}$$

$$[\alpha]=\begin{bmatrix}\cos\alpha & 0 & -\sin\alpha\\ 0 & 1 & 0\\ \sin\alpha & 0 & \cos\alpha\end{bmatrix}\quad[\beta]=\begin{bmatrix}\cos\beta & -\sin\beta & 0\\ \sin\beta & \cos\beta & 0\\ 0 & 1 & 0\end{bmatrix} \tag{22}$$

The winds in the NED system are then computed by:

$$\begin{bmatrix}V_{True\,North}\\ V_{True\,East}\\ V_{True\,Down}\end{bmatrix}=[\psi]\ [\theta]\ [\phi]\ [\alpha]\ [\beta]\begin{bmatrix}V_{true}\\ 0\\ 0\end{bmatrix} \tag{23}$$

$$\begin{bmatrix}V_{WindNorth}\\ V_{WindEast}\\ V_{WindDown}\end{bmatrix}=\begin{bmatrix}V_{TrueNorth}\\ V_{TrueEast}\\ V_{TrueDown}\end{bmatrix}-\begin{bmatrix}V_{INSNorth}\\ V_{INSEast}\\ V_{INSDown}\end{bmatrix} \tag{24}$$

The first and simplest method for computing the winds is from constant altitude, wings-level flight and an assumption of zero sideslip. For constant altitude, zero sideslip and wings-level flight, AOA can be assumed to be equal to pitch attitude.

$$\phi,\ \beta\ \ and\ \ \frac{dh}{dt}or\ \ \gamma=0 \tag{25}$$

$$\alpha=\theta \tag{26}$$

where:

ϕ = bank angle,
θ = pitch attitude,
α = angle of attack,
β = sideslip,
γ = flightpath, and
$\frac{\mathrm{dh}}{\mathrm{dt}}$ = rate of climb.

The winds are computed by using the previously mentioned algorithm and assuming that AOA is equal to pitch attitude and that sideslip is zero. Winds are held constant throughout the maneuver.

The second way to compute the winds involves solving a least-squares, nonlinear minimization problem. The vertical component of the wind is assumed to be zero and a scalar cost function is defined as:

$$J = \frac{1}{2}\sum_{i=1}^{N}\left[\left(V_{INS\ North\,i} + V_{Wind\ North\,i}\right)^2 + \left(V_{INS\ East\,i} + V_{Wind\ East\,i}\right)^2 - V_{true\,i}{}^2\right] \tag{27}$$

where:

$V_{\text{INS North i}}$ = i’th data point North INS velocity,
$V_{\text{INS East i}}$ = i’th data point East INS velocity,
$V_{\text{true i}}$ = i’th true airspeed data point, and
J = scalar cost function.

Any nonlinear, iterative, minimization procedure is then used to minimize the cost function to estimate the constant values for East and North winds. In theory, the vertical wind component can also be identified; however, the AFFTC has had little luck in trying to derive reasonable values for this parameter using the above method.

A third way to compute the winds assumes a separate measurement of true airspeed, AOA, and sideslip. This method is often used when INS/IMU derived air data are desired at conditions where classic calibrations of the measured vane and Pitot-static system values are not valid. The winds are computed while at flight conditions where the classical calibrations are valid and then held constant while maneuvering outside of these regions. A typical use might be during high AOA or departure testing where large values of AOA and sideslip can be expected. For High AOA, large variations in altitude can also be encountered; therefore, the winds are often computed and stored as a function of altitude during a wind-calibration climb up to the maneuver entry altitude. Winds are computed and tabulated as a function of altitude and then added appropriately to the INS/IMU velocities during the maneuver.

Once the winds are available in the NED system, the following can be used to compute the true airspeed, AOA and sideslip:

$$\begin{bmatrix} V_{xbody\ wind} \\ V_{ybody\ wind} \\ V_{zbody\ wind} \end{bmatrix} = [\phi][\theta][\psi] \begin{bmatrix} V_{Wind\ North} \\ V_{Wind\ East} \\ V_{Wind\ Down} \end{bmatrix} \tag{28}$$

$$\begin{bmatrix} V_{xbody\ \ INS} \\ V_{ybody\ \ INS} \\ V_{zbody\ \ INS} \end{bmatrix} = [\phi][\theta][\psi] \begin{bmatrix} V_{North\ \ INS} \\ V_{East\ INS} \\ V_{Down\ INS} \end{bmatrix} \tag{29}$$

$$V_{TrueINS} = \sqrt{(V_{x\,bodyINS} + V_{x\,bodywind})^2 + (V_{y\,bodyINS} + V_{y\,bodywind})^2 + (V_{z\,bodyINS} + V_{z\,bodywind})^2} \tag{30}$$

$$\beta_{true} = \arcsin\left(\frac{V_{y\ body\ INS} + V_{y\ body\ wind}}{V_{True\ INS}}\right) \tag{31}$$

$$\alpha_{true} = \arctan\left(\frac{V_{z\ body\ INS} + V_{z\ body\ wind}}{V_{x\ body\ INS} + V_{z\ body\ wind}}\right) \tag{32}$$

where:

$U_{\text{body wind}}$, $V_{\text{body wind}}$, $W_{\text{body wind}}$ = X, Y, Z body axis wind components,
$V_{\text{true INS}}$ = true airspeed computed from INS velocities and winds,
α_{true} = true AOA,
β_{true} = true sideslip, and
$V_{\text{xbody INS}}$, $V_{\text{ybody INS}}$, $V_{\text{zbody INS}}$ = INS body axis velocities.

5.3.7 Force and Moment Computations

Total applied forces and moments can be computed from the flight test data. Total applied forces (gravity is not an applied force) can be modeled with Newton's second law;

$$\sum \vec{F} = m\vec{A} = \vec{F}_{applied} + \vec{F}_{gravity} \tag{33}$$

$$\vec{F}_{applied} = \vec{F}_{aero} + \vec{F}_{thrust} = Weight \begin{bmatrix} N_{xcg} \\ N_{ycg} \\ -N_{zcg} \end{bmatrix} \tag{34}$$

where:

$\vec{F}_{\text{aero}}$ = vector of aerodynamic forces,
$\vec{F}_{\text{thrust}}$ = vector of thrust forces,
N_{xcg} = X body axis load factor,
N_{ycg} = y body axis load factor, and
N_{zcg} = -z body axis load factor.

The total applied force is computed from the flight measured (and corrected) load factors. In order to separate out the aerodynamic and thrust components, a thrust model and a gravity model are required. For most applications, assuming a simple scalar value for gravity (approximately 32.174 ft/s^2) is appropriate. For conditions where more accuracy is required, or the flat nonrotating earth equations of motion do not apply, a more complex gravity model may be required (*Evolution of Flight Vehicle System Identification,* Reference 8). The engine or thrust forces are usually computed from an engine model; the complexity required depending on the desired accuracy. A detailed propeller model may also be required for propeller-driven aircraft. The components from these models are then computed and subtracted from the measure applied forces to obtain the aerodynamic contributions.

$$\vec{F}_{aero} = Wt \begin{bmatrix} N_{xcg} \\ N_{ycg} \\ -N_{zcg} \end{bmatrix} - \vec{F}_{thrust} \tag{35}$$

where:

$\vec{F}_{aero}$ = vector of aerodynamic forces,
$\vec{F}_{thrust}$ = vector of thrust forces, and
Wt = weight.

When engine models are not available, the total forces as measured by an accelerometer will include both aerodynamic and engine components. Fortunately for most stability and control applications and with conventional aircraft, the engine forces are usually aligned parallel to the X-body axis and the aircraft normal and side forces will have minimal engine contributions. This is not the case for aircraft with large thrust offset or for thrust vectored aircraft. In these cases, some form of thrust model is required to separate aerodynamic and thrust forces.

The moment computations are developed in a similar fashion.

$$\sum \vec{M} = \vec{M}_{applied} = \frac{d\vec{H}}{dt} \tag{36}$$

$$\vec{M}_{applied} = \vec{M}_{aero} + \vec{M}_{thrust} + \vec{M}_{prop} \tag{37}$$

where:

$\vec{H}$ = vector of angular momentum,
$\vec{M}$ = vector of moments,
$\vec{M}_{applied}$ = vector of applied moments,
$\vec{M}_{aero}$ = vector of aerodynamic moments,
$\vec{M}_{thrust}$ = vector of thrust moments, and
$\vec{M}_{prop}$ = vector of propeller moments or other rotating component moments.

The aerodynamic component arises from either the basic flow about the aircraft or from deflection of control surfaces. The thrust moments arise from the alignment of the thrust vector with the aircraft cg. The propeller moments are direct torques applied from the rotating compressors, fans or propellers. These are usually small for a jet aircraft, but can be large for a propeller-driven aircraft.

Assuming that the inertias are constant over the time frame of interest, and that the two sources of angular momentum are the rotating body and rotating engine parts, the angular momentum is:

$$\vec{H} = I\vec{\omega} = I_b\vec{\omega}_b + I_{eng}\vec{\omega}_{eng} \tag{38}$$

where:

$\vec{\mathrm{H}}$ = angular momentum,
$\vec{\omega}_b$ = $[p, q, r]^T$ vector of body axis angular rates, and
$\vec{\omega}_{eng}$ = $[\omega_{xe}, \omega_{ye}, \omega_{ze}]$ vector of engine rotation rates in body axis.

Applying the appropriate rotating frame differentiation and assuming constant inertias:

$$\frac{d\vec{H}}{dt} = \dot{\vec{H}} + \vec{\omega} \times \vec{H} = I\frac{d\vec{\omega}}{dt} + \vec{\omega} \times I\vec{\omega} \text{ for constant I} \tag{39}$$

$$\frac{d\vec{H}}{dt} = I_b\frac{d\vec{\omega}_b}{dt} + \vec{\omega}_b \times I_b\vec{\omega}_b + I_{eng}\frac{d\vec{\omega}_{eng}}{dt} + \vec{\omega}_b \times I_{eng}\vec{\omega}_{eng} \tag{40}$$

Therefore, from Equation 36, the applied moment is:

$$\vec{M}_{applied} = I_b\frac{d\vec{\omega}_b}{dt} + \vec{\omega}_b \times I_b\vec{\omega}_b + I_{eng}\frac{d\vec{\omega}_{eng}}{dt} + \vec{\omega}_b \times I_{eng}\vec{\omega}_{eng} \tag{41}$$

Equation 41 requires the engine rotating component of the inertias, and aircraft body inertias as well as the respective angular rates and accelerations. Often the engine rotating rates are considered constant. The aerodynamic moments can be computed by subtracting model values of the thrust and/or propeller moments from the total applied moments.

$$\vec{M}_{aero} = \vec{M}_{applied} - \vec{M}_{thrust} - \vec{M}_{prop} \tag{42}$$

If significant, the thrust and propeller moments are usually computed from propulsive and propeller models. In some cases they can be directly measured (i.e., a torque meter on a propeller aircraft). For nonthrust vectored jet aircraft, with the thrust vector aligned approximately through the cg, Equation 42 will give a good approximation of the aerodynamic moments.

5.3.8 Aerodynamic Parameter Identification

One of the key aspects of the predict, test, update, and validate test method is the comparison of predicted and flight-derived aerodynamic models, combined with the updating of the predicted model based on test results. The science and art of aerodynamic parameter identification covers volumes of text and technical papers. Reference 8, *Evolution of Flight Vehicle System Identification*, gives an excellent overview of the subject. Reference 9, *Application of Parameter Estimation to Aircraft Stability and Control, The Output Error Approach*, gives technical details on algorithmic implementation. This section will cover a brief review of the different types of parameter identification and some of the necessary requirements for obtaining good results. Experience has indicated that obtaining good aerodynamic parameter estimates is as much an art as a science. While modern parameter estimation techniques have solid and well-founded mathematical roots, the actual application and use has been found to be as much a function of the knowledge and experience of the analyst as with the algorithm itself.

Modern aerodynamic parameter identification techniques are dependent on instrumentation, test techniques and data analyses methodologies. Each is critical and must be properly addressed in order to obtain acceptable results. Improper consideration in any of these areas can lead to poor parameter identification results.

The instrumentation system must be high fidelity with proper resolution, sample rates, filtering, and few or no unknown time delays between parameters. Poorly designed instrumentation systems will result in poor aerodynamic parameter estimates. Any aircraft state, control, or output parameter which is misrepresented by the instrumentation system will have cascading impacts on estimated aerodynamic derivatives. Resolution must be sufficient to catch the smallest increment in a state, control, or output, which is significant to the dynamics of interest. The resolution should also be finer than the expected noise characteristics. Likewise, range must be sufficient to catch the largest variation desired. Calibration must be of acceptable quality to ensure that the actual measured state, control, or output variable is as indicated. Sample rate is also key in aerodynamic parameter estimation. Reference 10, *Effects of Flight Instrumentation Errors on the Estimation of Aircraft Stability and Control Derivatives*, gives an excellent overview of the basic instrumentation requirements for aerodynamic parameter identification. One of the most potentially devastating impacts of an instrumentation system on parameter identification results is relative time delays and/or phase shifts between signals. There are several sources of potential time delays and phase shifts in sampled data systems. Pure time delays can arise when parameters are sampled serially within the allotted sample timeframe. They can also arise from communication across data buses or through multiple computers. Phase lag can be imparted by anti-aliasing filtering or any other type of analog or digital filtering. Phase lags produce an apparent time delay, which is a function of frequency of the signal, increasing the time delay with higher frequencies. Reference 11, *Effects of Time-Shifted Data on Flight Determined Stability and Control Derivatives*, gives an excellent accounting of the impacts of time delays on aerodynamic parameter identification results.

Flight test maneuvers must be designed to provide the appropriate response and frequency content for the maneuvers of interest. Maneuver duration and input sequencing must be considered. In addition, identifiability of the desired parameters must be ensured. As an example, a roll command input where both the ailerons and rolling-tail move in a linear dependent fashion will not produce sufficient information to identify both the aileron and rolling tail parameters. In this case, separate surface inputs (i.e., the PTI explained in Section 3) are required to provide sufficient information to derive the control powers for both the aileron and the rolling tail. The same will exist for any linearly connected parameter. The AFFTC has traditionally used the doublet maneuver derive flight test parameter estimates. The 3-2-1-1 maneuver is favored in Europe for parameter identification. The AFFTC method has traditionally used a 1- to 3-second duration symmetrical doublet. More recently, this has been modified to be a rapid (less than 1 second) input followed by the traditional doublet. The rapid movement was added in order to increase the high frequency content of the input. The 3-2-1-1 maneuver is a 3-second-square input in one direction, followed by a 2-second-square reversal, followed by a 2-second-symmetrical doublet. In addition to these types of maneuvers, the frequency sweep has also been used for parameter identification. The frequency sweep is generally used when parameter identification is being accomplished within the frequency domain; however, these maneuvers can also be used for time domain parameter identification.

There are three basic parameter estimation or identification techniques in use today. These are the equation error, output error, and filter error techniques. Reference 8 gives a good overview of these techniques.

The equation error technique typically matches the state or outputs rates in some fashion. This method sets up a form of a linear model of the dependent parameter as a function of the independent variable, and then produces estimates of the parameters with a least squares match;

$$\vec{Z} = H\vec{\theta} \tag{43}$$

where:

$\vec{\theta} = [\theta_1, \theta_2 \ldots\ldots \theta_n]^T$, vector of unknown constants,
$H = [h_1, h_2, \ldots h_n]$, vector of measures states, outputs, or inputs, and
$\vec{Z} = [Z_1, Z_2, \ldots . Z_n]^T$, vector of responses.

The least squares solution to find the constant parameters is:

$$\vec{\theta} = \left(H^T H\right)^{-1} H^T \vec{Z} \tag{44}$$

This method is simple, and requires neither integration nor iterations. The above solution in Equation 44 can be processed in either a batch or recursive fashion. The computations can be carried out quickly with modern computers. More advanced variations of this technique have also been used. The mathematical literature often berates the technique for being asymptotically biased as opposed to unbiased techniques using the other two methodologies. However, it has been successfully used in multiple instances. This method does require higher quality data and is more sensitive to the relative phasing of the measurements than do the other methods. In addition, the method is also more sensitive to noise than other techniques. For this reason, the data are often preprocessed through a trajectory reconstruction algorithm to estimate the states and outputs to ensure kinematic consistency of the measurements. This additional step can often reduce the benefits of the technique by complicating the analyses.

The output error method is perhaps the most common method in use today. This method is a nonlinear method that uses the aircraft equations of motion as well as statistical estimation of the measurement noise to estimate the aerodynamic parameters. Perhaps one of the best known of the algorithms is the Modified Maximum Likelihood Estimator (MMLE) (Reference 9) and its descendent Pest developed by the NASA Dryden Flight Research Center (DFRC). The aircraft dynamics are defined by a set of state rate, output and measurement equations (linear or nonlinear);

$$\begin{aligned} \frac{d\vec{x}}{dt} &= f\left(\vec{x},\vec{u},t\right) \\ y &= g\left(\vec{x},\vec{u},t\right) \\ z &= g\left(\vec{x},\vec{u},t\right)+v \end{aligned} \tag{45}$$

where:

$\vec{x}$ = aircraft state vector,
$\vec{u}$ = aircraft input vector,
$\vec{y}$ = aircraft output vector,
$\vec{z}$ = aircraft measurement vector,
$\vec{v}$ = measurement noise vector, and
t = time.

Given a set of constant parameters which define the system model:

$$\theta = \left[\theta_1 \quad \theta_2 \quad ..... \quad \theta_n\right] \tag{46}$$

A scalar cost function is defined which requires minimization:

$$J = \frac{1}{2}\sum_{i=1}^{N} = \left[\vec{Z}_{i\,measured} - \vec{Z}_{i\,estimate}\right]^T R^{-1}\left[\vec{Z}_{i\,measured} - \vec{Z}_{i\,estimate}\right] \tag{47}$$

where:

J = scalar cost function,
$\vec{Z}_{imeasured}$ = vector of i’th measurement,
$\vec{Z}_{imeasured}$ = vector of i’th estimated measurement,
R = measurement covariance matrix, and
I = index of measurements.

The estimated values in Equation 47 are computed by the model with the latest parameter updates and the measured parameters are the instrumented states and outputs. The matrix R is the noise covariance matrix for the instrumented parameters. A solution for a new update vector is:

$$\vec{\theta}_{new} = \vec{\theta}_{last} + \vec{\delta}_{\theta} \tag{48}$$

$$\vec{\delta}_{\theta} = \vec{\theta}_{last} - \left[\frac{\partial^2 J}{\partial \vec{\theta}^2}\right]^{-1} \frac{\partial J}{\partial \theta} \tag{49}$$

$$\frac{\partial J}{\partial \theta} = \sum_{i=1}^{N}\left[\vec{Z}_{i\,measured} - \vec{Z}_{i\,estimate}\right]^T R^{-1} \frac{\partial \vec{Z}_{i\ \ measured}}{\partial \vec{\theta}} \tag{50}$$

$$\left[\frac{\partial^2 J}{\partial \vec{\theta}^2}\right] \approx \left[\frac{\partial \vec{Z}_{i\ \ measured}}{\partial \vec{\theta}}\right]^T R^{-1}\left[\frac{\partial \vec{Z}_{i\ \ measured}}{\partial \vec{\theta}}\right] \tag{51}$$

where:

δ_θ = vector of updates to parameters,

$\left[\frac{\partial \mathrm{J}}{\partial \theta}\right]$ = gradient of cost function wrt the parameters,

$\left[\frac{\partial^2 \mathrm{J}}{\partial \vec{\theta}^2}\right]$ = approximated second gradient of cost function wrt the parameter, and

$\left[\frac{\partial \vec{\mathrm{Z}}_{\mathrm{i\ measured}}}{\partial \vec{\theta}}\right]$ = gradient of the measurements wrt the parameters.

The gradient of the measurements with respect to the parameters is normally computed numerically for nonlinear applications. In some instances, the gradient can be computed analytically. The MMLE method is the most used and has been in practice at the AFFTC and DFRC since the mid 1970's and has proven to be extremely powerful.

The third method, filter error, accounts for both the process as well as measurement noise. This method most commonly applies a Kalman filtering technique to estimate the aircraft states, outputs and measurements based on measured inputs, and then updates the estimated states and outputs based on a proportional difference between the estimated and measured parameters. The constant of proportionality is the Kalman gain matrix. The aircraft dynamics are modeled similar to those of the output error method, with the exception that process noise is present.

$$\begin{aligned} \frac{d\vec{x}}{dt} &= f\left(\vec{x},\vec{u},t\right)+\vec{\gamma}(t) \\ y &= g\left(\vec{x},\vec{u},t\right) \\ z &= g\left(\vec{x},\vec{u},t\right)+\vec{v}(t) \end{aligned} \tag{52}$$

where:

$\vec{\mathrm{x}}$ = aircraft state vector,
$\vec{\mathrm{u}}$ = aircraft input vector,
$\vec{\mathrm{y}}$ = aircraft output vector,
$\vec{\mathrm{z}}$ = aircraft measurement vector,
$\vec{v}$ = measurement noise vector, and
t = time.

The state vector now contains the unknown parameters as well as the aircraft states. The state vector is also augmented with process noise.

The general update equation is;

$$\vec{x}_{new} = \vec{x}_{estimated} + K\left[\vec{z}_{measured} - \vec{z}_{estimated}\right] \tag{53}$$

where:

$\vec{\mathrm{x}}_{\mathrm{new}}$ = updated estimated state vector,
$\vec{\mathrm{x}}_{\mathrm{estimated}}$ = last estimated state vector,
$\vec{\mathrm{z}}_{\mathrm{measurement}}$ = actual measurement vector,
$\vec{\mathrm{z}}_{\mathrm{estimated}}$ = estimated measurement vector, and
K = Kalman Gain matrix.

The estimated values of the states and measurements are extrapolated from the current time point to the next time point by integrating the state-rate equations. The states are then updated using the Kalman Gain matrix and the difference between the actual and the estimated measurements. The computation of the

Kalman Gain matrix involves the co-variances of both the process and measurement noise and the covariance of the overall error. The covariance of the overall error changes with time and hence is extrapolated and updated from the current to the next time point much as are the states. The details of this operation and the updating of the Kalman Gain matrix are beyond the scope of this document. Reference 12, *Applied Optimal Estimation,* gives details on the computation of Kalman Gain matrix and the covariance propagation for both linear and nonlinear systems. This method is not widely used in direct aircraft aerodynamic parameter estimation due to the sensitivity of the answers to process and measurement noise. Obtaining accurate values for both the process and measurement noise covariance is difficult in most practical flight test applications. However, if reasonable values for both the process and measurement noise can be determined, this method can produce excellent results.

Both the output and filter error methods are designed to accommodate noise. The output error method specifically assumes that there is no process noise (i.e., there is no uncorrelated noise in the aircraft states such as turbulence). The method assumes that all the noise exists in the measurements and that it is white noise with zero mean, and a known covariance with a Gaussian distribution. The filter error method is designed to include the process noise, but makes similar assumptions that the noise is white zero mean and Gaussian. Measurement noise can be assumed to be added by the instrumentation system, and for a well designed system the assumption of white noise contamination is reasonable. However, almost no noise in aircraft data are purely white, and the degree that the assumption is violated will degrade the analytical results. As an example, turbulence is not white noise, it also has no correlated input, but does show up in the measured aircraft response. Another example of nonwhite noise is aircraft buffet and structural modes. Both of these can be picked up by the instrumentation system and each are likely to have a well defined frequency band through which they operate. Noise, either process or measurement, will inherently degrade parameter estimates.

5.3.9 Frequency Response Analyses

Frequency response analyses is another form of parameter, or more accurately, systems identification. Rather than identify specific parameters, the method is used to identify system characteristics such as transfer functions. However, the method can be expanded to include individual parameter identification and has been widely used for this purpose in rotary wing aircraft. In this document, we will confine the discussion to the more classical use in system as opposed to parameter identification.

The method applies the discrete FFT to the flight data to transform from the time to the frequency domain. Frequency response methods assume linearity, and are limited to estimating systems where linear approximations are valid. The FFT is based on the classical Fourier Transform, where a time domain signal is transformed into the frequency domain with the following;

$$y(j\omega_k) = \frac{2}{N}\sum_{n=0}^{N-1} y_n e^{-j\frac{2\pi kn}{N}} = a_k + jb_K \tag{54}$$

where:

k = index of frequencies,
N = number of points,
n = index of time points,
T = time length of time history,
J = $\sqrt{-1}$,
E = exponential operator, and
$\varpi_k = \frac{2\pi}{T}$.

From this discrete transformation, the magnitude and phase relationships for a given signal can be generated from;

$$Mag_k = \sqrt{a_k{}^2 + b_k{}^2} \tag{55}$$

$$Phase_k = \frac{\pi}{2} + \tan^{-1}\left(\frac{b_k}{a_k}\right) \tag{56}$$

The method is limited in the range of frequencies which can be discretely analyzed by the following relationships;

$$Highest \quad frequency = \frac{\pi}{\Delta T} \tag{57}$$

$$Lowest \quad frequency = \frac{2\pi}{T} \tag{58}$$

where:

ΔT = sample rate and
T = total time.

Higher frequency bands of interest require higher sample rates as determined by the Nyquist frequency. In addition, if significant lower frequency content is desired then the maneuver must be of sufficient length. Both are considerations in using the FFT for aircraft systems identification. Maneuver length can be adjusted to provide the low frequency content; however, the high frequency content will be limited by the instrumentation system. If high frequency content is desired for postflight data analyses, then the sample rate of the instrumentation system should be set accordingly.

As previously mentioned, the method assumes linearity. The degree of nonlinearity in the system under analyses will determine the robustness of the analyses. Nonlinearities such as non-proportional response, dead bands, hysterisis, and saturation will degrade the analyses, and if severe enough, can invalidate the analyses. Care must be exercised to ensure that the test maneuvers and conditions will maintain sufficient linearity in order to achieve valid frequency response data.

Linear systems can often be described using transfer functions. A transfer function is a linear operator which describes the magnitude and phase relationship ratio between the input and output. When multiplied by a given input, the transfer function gives the system output:

$$\text{Output} = (\text{TransferFunction})\ \text{Input} \tag{59}$$

$$\text{Transfer Function} = \frac{\text{Output}}{\text{Input}} \tag{60}$$

The two most common outputs from the FFT analyses are a PSD of individual signals, and either Bode or Nyquist plots of amplitude and phase relationships between two signals. The PSD is used to examine the frequency content of a signal and the Bode or Nyquist plots are used to analyze the frequency response of a transfer function. The PSD plots can be used to examine the frequency content of a signal for such analyses as determining appropriate filtering, identifying structural or other modes in the data, identifying noise characteristics and aliased signals. The Bode and Nyquist plots are often used to compare the actual system response for key handling qualities transfer functions to published criteria These criteria are often represented in the frequency domain, and FFT-type analyses allows direct comparison to the criteria. This is often preferable to the alternative of using aerodynamic parameter identification combined with FCS models to generate the desired Bode or Nyquist plots for comparison. The FFT method is a direct measurement and reduces the impacts of modeling errors.

The transfer function method has also been used to determine pseudo open-loop stability margins during envelope expansion. The method is labeled as a pseudo open loop since the loop is not truly opened, but instead is manipulated in a fashion to derive the open-loop characteristics. Figure 20 shows a typical set up for this type of analyses.

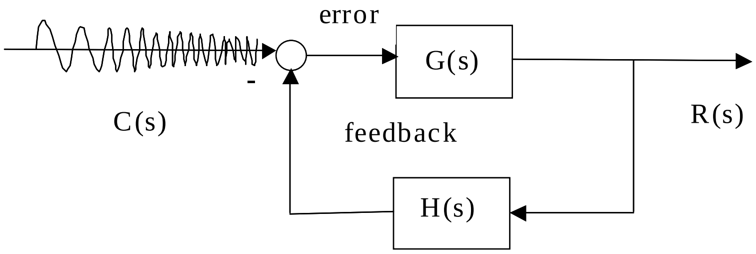

Figure 20 Typical Closed-Loop System With Sinusoidal Input

Reference 14, *Real-Time Open-Loop Frequency response Analysis of Flight Test Data*, gives an excellent overview of determining pseudo open-loop stability margins from flight test data. This method is applicable when a single input single output (SISO) path can be defined within the FCS to apply the analyses. For the case shown in Figure 20, the transfer function input is the error signal and the output is the feedback signal. For multiple input, multiple output (MIMO) systems, the application becomes more difficult. A classical example of this would be in the lateral directional FCS axis, where coupling between roll and yaw commands and feedbacks are common. In this case, the commands to a given actuator (i.e., rudder or aileron) are often used as the summing junction. Comparison would then be made with predictions which open only the loop in question with all other loops closed. Care must be taken to ensure that the analyzed loops from flight test are similar to those used for the predicted characteristics. The technique requires that a unique input signal be designed to produce the pseudo open loop transfer function by comparison with the command and feedback paths. Without this separate signal for comparison, the signal will return the gain and phase characteristics of the summing junction. This also implies that the applicable bandwidth of the analyses will depend on the bandwidth of the input signal.

The input signals are often derived from high bandwidth maneuvers such as target tracking or other handling qualities tasks. Maneuvers such as HQDT usually provide sufficient bandwidth to obtain closed loop transfer functions pertinent to handling qualities criteria comparison. However, pilot bandwidth is limited to a maximum of approximately 30 radians per second with less than 20 radians per second the norm. If higher bandwidths are desired, then some other type of input besides that generated by the pilot may be required. The automatically generated swept sine sweep is often used to provide the input signal for frequency response analyses. The swept sine sweep is usually generated from special flight test function generator and combined directly into the FCS at appropriate junctions for the analyses desired. This technique will not provide a direct measurement of the pilots input at the stick or rudder pedals. For analyses requiring this input, a pilot induced swept sin sweep is generally used. The frequency content, magnitude and duration of the preprogrammed swept sine sweep should be optimized from simulation tests combined with an FFT analyses routine. The piloted swept sin sweep should also be practiced in the simulation to ensure adequate content and duration.

5.3.10 Trajectory Reconstruction

Trajectory reconstruction is a postflight simulation technique, similar to aerodynamic parameter identification, which attempts to define the best estimate of the true aircraft trajectory (states and outputs) based on flawed measurements. The technique estimates the true trajectory, the measurement errors and provides kinematically consistent aircraft states and outputs for other analyses. It can also be used to estimate states or outputs which are not directly instrumented. Reference 15, *Identification of the Aerodynamic Model of the DLR Research Aircraft (ATTS) for Flight Test Data*, gives information on the trajectory reconstruction process.

Trajectory reconstruction integrates the aircraft equations of motion driven by flight test measured inputs to derive the estimated states. Rather than use aircraft control inputs and an aerodynamic model to drive the equations of motion, trajectory reconstruction directly uses measured accelerations and axis rates as inputs. The equations of motion can be formulated to use accelerations and rates as inputs as opposed to aerodynamic or thrust generated forces and moments. Trajectory reconstruction requires a postulated measurement error model to estimate parameter errors. Combining these into a simulation and parameter estimation routine allows for an estimation of the true trajectory of the aircraft.

The equations of motion are of the form:

$$\begin{aligned} \frac{d\vec{x}}{dt} &= f\left(\vec{x},\vec{u},t\right) \\ \vec{y} &= g\left(\vec{x},\vec{u},t\right) \end{aligned} \tag{61}$$

where:

$\vec{x}$ = state vector,
$\vec{u}$ = input vector, [$p_{measured}$, $q_{measured}$, $r_{measured}$], [$Nx_{measured}$, $Ny_{measured}$, $Nz_{measured}$],
$\vec{y}$ = output vector, and
t = time.

Similar to the parameter estimation case, a constant vector of unknowns and a scalar cost function are defined;

$$\vec{\theta} = \left[\theta_1 \quad \theta_2 \quad ..... \quad \theta_n\right] \tag{62}$$

$$J = \frac{1}{2}\sum_{i=1}^{N} = \left[\vec{Z}_{i\,measured} - \vec{Z}_{i\,estimate}\right]^T R^{-1}\left[\vec{Z}_{i\,measured} - \vec{Z}_{i\,estimate}\right] \tag{63}$$

where:

$\vec{\theta}$ = unknown parameter vector,
J = scalar-cost function,
$\vec{Z}_{imeasured}$ = vector of i’th measurement,
$\vec{Z}_{imeasured}$ = vector of i’th estimated measurement,
R = measurement covariance matrix, and
I = index of measurements.

The above is an output error formulation. The trajectory reconstruction problem can also be formulated in a filter error or Kalman Filter approach. The Kalman Filter approach is especially well suited for the trajectory reconstruction problem.

Trajectory reconstruction differs from aerodynamic parameter estimation in the form of the measurement model. For trajectory reconstruction, an attempt is made to model all of the errors in the instrumentation system, then identify these errors as the unknown parameters. The estimated measurement model is often set up as a simple bias and slope model;

$$\vec{Z}_{measured\ estimate} = (1+k)(\vec{Y}_{estimate} + \vec{Y}_{bias}) \tag{64}$$

where:

$\vec{Z}$ measured estimate = estimated measurement,
k = scalar error in the measurement,
$\vec{Y}$ estimate = estimated true value, and
$\vec{Y}$ bias = bias in the measurement.

The measurement model can also include more complicated models such as off cg corrections to accelerometers and vanes and sensor misalignments. Trajectory reconstruction attempts to match the actual measurements while identifying the model errors. Since the estimated measurement model is a function of the estimated states and outputs, when convergence occurs, the estimated states and outputs are assumed to be the best estimates of the actual states and outputs.

Trajectory reconstruction is often recommended prior to performing aerodynamic parameter identification. This is particularly true of the equation error methodologies. Both the output and filter error techniques allow for a formulation of the measurement equations similar to that used for trajectory reconstruction, thus allowing the reconstruction to be accomplished at the same time as the parameter estimation. The equation error method depends heavily on knowing the states and state rates of the system. Use of trajectory reconstruction can allow for the use of estimated states and state rates, which have lower uncertainty levels than direct but corrected measurements (corrected by methods in described above). The methodology can also produce estimated trajectories, which have higher uncertainty than the direct, corrected measurements.

5.4 Data Analyses Flow

5.4.1 General

Much of the philosophy described in this paper relies heavily on data analyses as the program progresses. A smooth, responsive analyses process is required in order for the predict, test, update, and validate philosophy to provide significant benefits. As with all other aspects of testing, early development and checkout of the data analyses system is essential to ensure that the proper data are available when needed during the execution of the test program. Failure to properly plan, develop, and test the data acquisition and analyses systems is one of the most common stumbling blocks encountered during flight test program execution. Insufficient planning and development in this area can lead not only to significant slowing of the test objective accomplishment, but can also have adverse safety implications.

5.4.2 Data Flow Planning

Figure 21 describes a basic data flow process from acquisition onboard the aircraft to the final analysis results. There should be a detailed data analyses plan developed for each discipline, and then an overall plan for all disciplines. The data analyses planning is as important as the flight test planning and should be worked early enough to allow for system development and testing prior to the execution of the flight test program.

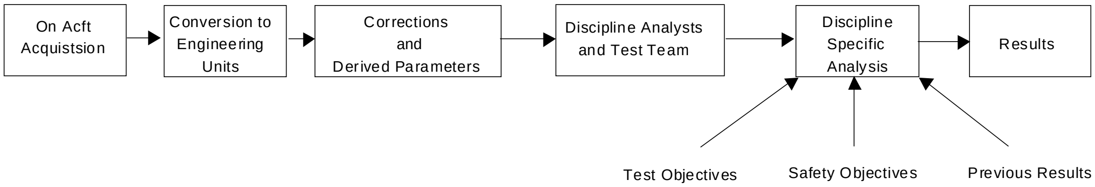
On Acft Acquistsion
Conversion to Engineering Units
Corrections and Derived Parameters
Discipline Analysts and Test Team
Discipline Specific Analysis
Results
Test Objectives
Safety Objectives
Previous Results

Figure 21 Typical Data Analyses

The data from the aircraft are converted from raw measurements (e.g., voltages and frequencies) to usable engineering units, then the appropriate corrections (e.g., position error, accelerometers off cg, and AOA vane corrections) are accomplished, derived parameters are computed (e.g., weight, cg, and inertias) and then the data are sent to discipline-specific analysts and the test team. The analysts and test team then perform further analyses based on the test and safety objectives as well as prior test results. The flow chart of Figure 21 should be replicated and further detail included for each specific engineering discipline as part of the test planning process. The detail should extend to the accuracy and calibrations for the on aircraft sensors, detailed analyses routines for corrections and test and safety objective accomplishment. The level of detail should include equations, software specifications and types of simulation required. As with the flight test plan, the data analyses plan must be flexible. The test team must be prepared to modify the plan and systems necessary to achieve the flight test objectives.

5.4.3 Data Flow Testing

Equally important as the data analyses planning process is the algorithm testing process. Data acquisition and analyses systems require developmental testing just as any other engineering system. This includes feedback of test results into the planning and development of the system as is shown in Figure 22.

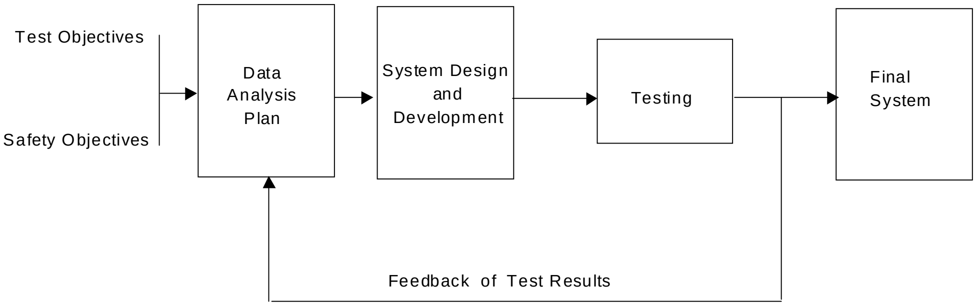

Figure 22 Analysis System Test Process

One of the most common mistakes is to underestimate the time and resources required for developing and testing the data analyses system. As a consequence, the data analyses system testing often gets short changed as the basic development takes longer than anticipated and the actual flight portion of the test program nears. The test team must ensure that adequate and timely resources are put toward the development of the data analyses system to ensure an adequate process such as that indicated in Figure 22 is accomplished.

One of the biggest problems in applying a data analyses system test process is obtaining input data for the systems testing, especially since there may not be any aircraft data available. There are several sources for obtaining data for the testing portion of the development. Previous flight tests on like or similar aircraft can provide one source. Another source is to model the potential corrections (e.g., position errors, off cg accelerometers, and vane indicated angles) in the simulator and use simulation data. These data may be intentionally corrupted with noise and also modified to indicate off predicted performance in order to more accurately reflect actual flight data. Such data can be routinely captured during other planning uses of the simulation. However, this capability requires advanced simulation planning in order to modify the simulation to provide the needed data.

The onboard aircraft portion of the acquisition system should be tested as soon as components of the system are available and continue until installed in the aircraft. Actual recording and telemetering can be tested to some extent on the ground before flight; however, the final test is usually the first few flights. One of the areas where future modeling and simulation efforts may be of large benefit is in modeling the on-aircraft portion of the data system. As research and development continues in the modeling and simulation field concerning electronic, software and spectrum transmission systems, the results may provide a huge benefit into developing the on-aircraft, recording, and telemetering portion of the data acquisition and analyses systems.

Another factor in reducing the amount of development and testing time for the data analyses system is to use tested and validated algorithms. Most flight test organizations have a reuse policy in place in order to reduce the overall data acquisition and analyses development time and cost. One of the historical problems with reuse libraries has been in maintenance and modernization. Any such library needs constant maintenance and modernization such that it can keep up with the demands of changing technology. Legacy hardware and algorithms can quickly become outdated in today's fast changing computer environment. Failure to maintain and modernize reuse libraries and systems may negate the benefits of said systems.

5.4.4 Data Analyses Flow Execution

Once the full development cycle for the system as indicated in Figure 21 has been accomplished, and the initial flight tests indicate that the system is working properly, then it is ready for production use. The primary objective of any data analyses system is to obtain and analyze the data as quickly as possible. The pace of the flight test program is often dictated by the pace of the applicable data analyses. A validated, efficient and timely data analyses flow is required for any flight test program to proceed on schedule and within budget. Required data analyses should be prioritized with respect to criticality relative to the current testing. The data analyses needs to be prioritized such that critical information is readily available, while less critical is done at some future date. This will be an ever-changing process as current test results will dictate changing prioritization. The test team must remain flexible in their analysis prioritization. Another way of significantly speeding up the analysis cycle is to perform as much of the analysis in real time as possible. This is becoming increasingly technically feasible as computer systems grow almost exponentially in capability. Designing the system such that many of the corrections and detailed discipline analysis can be conducted in real time or near real time (soon after collection or maneuver execution) will have a large beneficial impact on test efficiency and safety.

5.5 Data Tracking and Databases

5.5.1 General

Large amounts of data are typically collected during the course of a DFCS flight test program. Furthermore, the final reporting may not take place until years after the start of the test program. Both of these circumstances require that the data collected be thoroughly catalogued and easily retrieved. This requires a sophisticated data tracking and databasing system. The job is made easier by taking advantage of commercially available software specifically designed for data-tracking and databasing. The importance of a databasing and tracking system cannot be over emphasized.

5.5.2 Data Tracking

Data tracking is the process of tracking what maneuvers have been performed, what data were collected and what the quality of the data were. This information is essential in tracking test objective progression and in defining any needed retest. When large amounts of data are collected, it is easy to lose track of what has been accomplished and what data are available. A user friendly data-tracking system is required in order to manage the test plan, program progress and data analyses.

The tracking system should identify the specific test points, their relationship to the test plan and information on maneuver and instrumentation quality. It should also contain information concerning test-point completion. Completion should be defined as sufficient quantity and quality of data available in order to consider the point accomplished relative to its relationship to the test objectives. The test team should avoid labeling a test point complete simply by having performed it on a mission. Sufficient analysis must be completed to ensure that the data quality and quantity standards are met. The data tracking system should be automated as much as practical, although complete automation is not possible. Any system will require inputs from the test team as to whether the individual test point is complete. The system should also be capable of interfacing with the databasing system to ensure that the final stored information on any given point is up to date and complete.

5.5.3 Databasing

Databasing is the actual storage for later retrieval and use. As with data tracking, the accumulation of large amounts of data makes it easy to lose track of what data are available, what file names they are stored under, and what conditions they represent. A well-designed databasing system will make the access and use of the data more efficient. Many past test programs have collected rooms full of data, but have developed no system for cataloguing these data. As a consequence, much of the data has become useless since there is no documentation as to specifically what the data represented. A usable databasing system needs to not only store the pertinent data for analyses, but also have higher level information concerning the flight number, specific maneuver, what is the flight condition and configuration, and whether or not the data quantity and quality are sufficient to support the test objectives. These higher level data are similar to those required for the data tracking system, hence, the need for an interface between the two systems.

The system needs to be user friendly and readily accessible by the entire test and analysis team as well as outside sources. It also needs to be capable of storing and tracking all analysis, from the engineering units conversion to the final reporting data. This should include not only time history data, but also detailed analysis, charts, intermediate analysis and the algorithms used. It should be possible to track the entire analysis trail via the databasing system. Without these capabilities, the management of large amounts of data collected in modern DFCS test programs is extremely difficult, if not impossible.

The test team should start planning the databasing system early in the test planning process. There are many commercial and independently developed databasing systems available in today’s market which have the required capability, so a large databasing system development program is not always required. The test team needs to define the databasing requirements early and investigate the needs for procurement or development early in the test planning process.

6.0 CONCLUDING REMARKS

This document has covered a wide range of subjects which are applicable to the flying qualities flight testing of DFCS. By necessity, the technical depth and disciplines involved in testing such systems covers a wide range of specialties. The job of flight testing a DFCS is really that of a systems development and integration problem. The DFCS depends on many other aircraft characteristics, systems, and subsystems in order to operate properly and perform its intended mission. Each must perform adequately in order for the entire DFCS to properly operate.

This report has covered specific areas deemed especially important by the author, specifically, the test preparation and data analyses sections. Proper preparation and data analyses are cornerstones of any successful flight test program, and as such have been given broad attention in this report. In addition, the consequences of potential mistakes while testing a DFCS can be disastrous, leading to loss of aircraft or life. Since this type of flight testing is often hazardous, it is incumbent on the test team to carefully plan and execute the program. The test team must be knowledgeable about what the aircraft is predicted to do, what it is doing, and the reasons for both. Armed with this knowledge, the DFCS flight test team can make the appropriate decisions required during the execution of the test program. Without minimizing the other areas involved, the author believes that preparation and data analyses are the two most important aspects of testing hence the emphasis on these areas.

Lastly, the procedures and practices presented in this report are a compilation of best practices as learned over the years by the test community. They certainly are neither exhaustive nor all-inclusive, simply a list of perhaps the most commonly used practices. There never has been, nor will there ever likely be, a test program where it is possible or practical to employ all of the practices discussed in this report. However, it is hoped that the target audience will find many of the practices applicable to their test programs and be able to improve both test efficiency and safety as a result.

7.0 ACKNOWLEDGEMENTS

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APPENDIX A

FRENCH EXPERIENCE

BY: TERRY D. SMITH

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1.0 FRENCH EXPERIENCE

In France, studies into digital flight control systems began in 1970. Prior to that date, aircraft such as the Mirage III and IV had conventional hydromechanical flight control system (FCS) with simplex analogue limited authority autostabilizers to augment basic handling qualities.

The move to multiplex analogue FCS resulted in the Balzac V and Mirage III-V being equipped with triplex analogue augmentation systems. A Mystere 20R was used as a full 6 axis in-flight simulator in a supporting research and development program. By the 1970’s, the Mirage G and G8 were flying with full authority multiplex analogue FCS.

By the late 1970’s, research using the Mystere 20R had resulted in the development of a hybrid digital/analogue FCS for the Mirage 2000, 4000 and 3NG aircraft. The digital functions involved elaboration of gains and air data computation but the FCS was fundamentally a quadruplex analogue system.

In the mid-1980’s a development of the Mirage 2000 known as the M2000 NUM was planned whereby the essentially analogue FCS was to be replaced by a full authority digital system to be fitted to the second prototype M2000. This project proceeded to the bench test phase but never flew. The project was overtaken by the Rafale A program and terminated when the second prototype M2000 was written off in an accident.

The Rafale A, which first flew in July 1986, was a technology demonstrator with the additional task of optimizing the aerodynamic configuration for the full Rafale development program. It was the first French aircraft with full authority digital FCS. The main Rafale flight test program commenced in 1991 with the first flight of the Rafale C. This was followed by the Rafale M and B variants.

The Rafale FCS is a full authority digital system in a longitudinally unstable aerodynamic configuration. The FCS was designed to control an aerodynamic configuration that was optimized from aerodynamics, buffet, lift, drag, structural loads, and control surface loads considerations.

The FCS functionality provides 6 axis stability augmentation on ground and in the air including gust alleviation. Handling qualities are optimized to give carefree handling and structural protection by controlling incidence sideslip, normal acceleration, roll rate and roll acceleration. Autopilot functions are included, which utilize novel inceptors such as brake pedals to provide input commands.

The FCS processes all the air data sensor inputs and is integrated with the avionic and weapon delivery systems in the provision of general navigation, terrain following, auto approach and landing (for both land and carrier based operations), and auto weapon delivery functions.

The FCS was designed with the safety specification requirement for a failure rate better than 10^{-6} per flying hour. This requirement included the FCS, hydraulics, and electrical supply system. The redundancy of the system is either quadruplex, triplex, or duplex depending upon the criticality of the subsystem. For example, quadruplex functions include inertial sensors, actuator-loop control, and moding status whereas air data is triplex.

Digital computing is triplex with duplex analogue backup computing and duplex interface computing for avionics, weapon system bus interfaces, and engine control computing. Two hydraulic systems plus an electrohydraulic pump and four electrical supplies (of

which two are dedicated to the FCS) are provided.

1.1 Flight Clearance Process

The methodology used for critical software is outlined in the Figure A1.

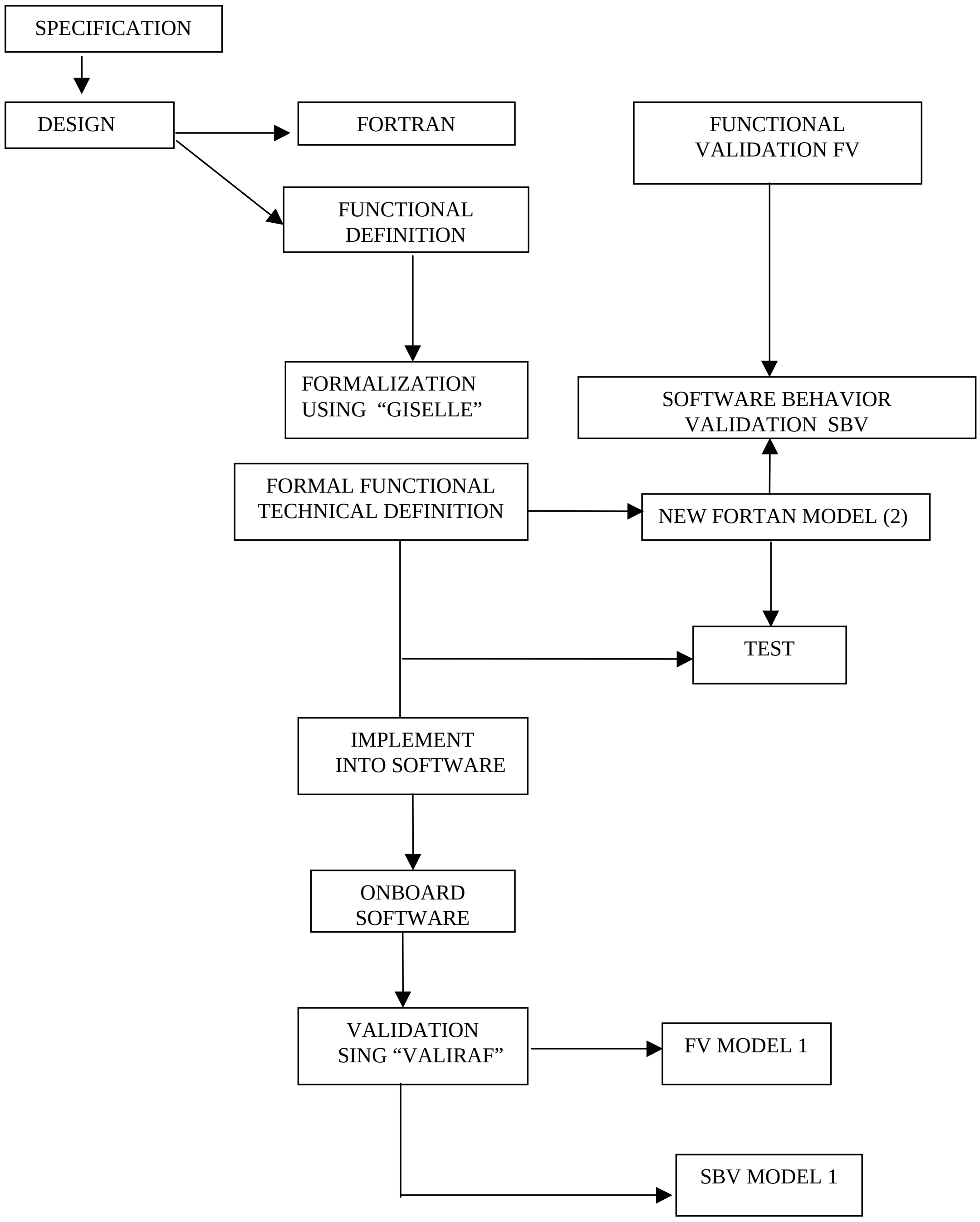
SPECIFICATION
DESIGN
FORTRAN
FUNCTIONAL VALIDATION FV
FUNCTIONAL DEFINITION
FORMALIZATION USING "GISELLE"
SOFTWARE BEHAVIOR VALIDATION SBV
FORMAL FUNCTIONAL TECHNICAL DEFINITION
NEW FORTAN MODEL (2)
TEST
IMPLEMENT INTO SOFTWARE
ONBOARD SOFTWARE
VALIDATION SING "VALIRAF"
FV MODEL 1
SBV MODEL 1

Figure A1 Critical Software Methodology

Flight clearance testing was performed on test benches that could be linked together. A full Iron Bird facility was not used.

For flight clearance testing, a decision was taken not to use an Iron Bird, but to use a series of test benches that could be used in isolation or linked together. This was considered to give more flexibility. The test benches were made up of an actuator bench, a flight control computer bench, a cockpit mounted in a dome simulation facility, and a simulation computer containing both the aerodynamic model and an FCS model. All testing was accomplished using these facilities. Integration testing had to be done using a number of different facilities.

The fact that no Iron Bird was utilized led to the philosophy of partial integration testing on each of a number of different system test facilities. Thus to ensure full integration across all systems, an overlap philosophy was used to ensure a full-integration assessment before equipment was fitted to the aircraft.

The fundamental clearance philosophy was that any change to the software would require a complete reclearance. Thus the flight development test plan identified a series of phased software releases. Each software upgrade contained new facilities and would also incorporate any changes required as the result of flight experience.

1.2 Flight Test

Flight test engineers and pilots were involved in the FCS design definition stage as well as the bench test phase leading to clearance for flight. This ensured that the required flight test facilities were provided within the FCS functionality.

1.3 Instrumentation

Data for flight test instrumentation (FTI) is obtained from the FCS with typically 250-300 signals being recorded. In order to maintain system integrity, the FTI interfaces with only 1 flight control computer flight control computer (FCC), but within that interface, all lanes of sensor data can be accessed. The FTI also interfaces with the data buses which are utilized by the FCS so has access to all consolidated FCS data output by the FCS.

Although FCS data are 32 bit, only the most significant bits are transmitted. Data are telemetered for a ground display and recording and are also recorded onboard the aircraft.

1.4 FCS Test Facilities

Test facilities are provided which contain a number of functions. These are comprised of:

a. Low frequency test input to cover the 0 to 5Hz range for aerodynamic data gathering and air data calibration purposes.

b. High frequency test inputs to cover the range 5 to 50 Hz for structural mode/flutter testing.

c. Ability to vary specific gains within the control laws. Only a very small number of gains could actually be varied (i.e., typically slat per degree AOA and stick command path gains) due to the extensive impact on flight clearance requirements.

1.5 Flight Test Philosophy

The basic objective of the flight test development program was to gather data that enable the various models used in the design process to be adjusted where necessary and thus validated. A step by step approach was used such that functions were progressively added to the FCS at each software upgrade and assessed/validated in flight before the next major upgrade.

Where functions could not be fully tested on the ground, the final assessment was performed in flight. The sidestick controller was an example of this. Considerable ground testing was completed prior to flight, but the final assessment could only be covered in the full-flight environment.

The number of possible FCS failure modes (reconfigurations) was deliberately kept to a minimum in the design phase in order to minimize the amount of ground clearance testing and flight testing. This flight testing of failure modes was limited to the significant reconfiguration states of loss of incidence/sideslip date and reversion to analogue backup mode. No flight assessment of failure transients by injecting failures was planned due to the complexity of the FCS. All such failure testing was performed on the test bench where the test philosophy required an assessment of all failures with a probability greater than 1 in 10^{-8} per flight hour.

1.6 Certification Philosophy

The flight test process was to be used to demonstrate compliance with the specification by validating the various models used in the design process and hence supporting predicted performance obtained from the theoretical and ground test results.

1.7 Digital FCS Issues

a. Validation of software.

b. Possibility of using software.

c. Very strict clearance methodology.

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APPENDIX B

GROUND AND FLIGHT TESTING DIGITAL FLIGHT CONTROL SYSTEMS IN THE UNITED KINGDOM

PAPER AUTHORED BY

TERRY D. SMITH

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GROUND AND FLIGHT TESTING DIGITAL FLIGHT CONTROL SYSTEMS IN THE UNITED KINGDOM

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1.0 INTRODUCTION

The final proof of design of any control system is the demonstration of successful integration of the control system into the total vehicle of which it is a part. Such a demonstration of satisfactory and therefore safe design must include an assessment of the behavior of the vehicle and its control system over the full range of normal and extreme environmental conditions to which it will be subject. Thus, in the case of an aircraft flight control system (FCS), this can only be achieved by testing the FCS when it is fully integrated into the aircraft and assessing it over the full operating envelope of the aircraft. Flight testing represents the ultimate proof that the design of the FCS is both fit for purpose and meets the design requirements.

Historically, the flight test process has been viewed as an independent check of the whole aircraft and its systems by the flight test team of pilots and engineers whose task was to assess the aircraft behavior and identify any problems with the design. Any problems identified had to be understood and resolved by the designers, and then the modified aircraft reassessed by the flight test team. Up to the 1950’s, the amount of flight data obtained from test flights was comparatively small and was made up of a combination of pilot’s notes (on a kneepad), photographs of banks of gauges, and data recorded on ultraviolet trace recorders that typically would record 10 parameters per recorder. Extraction of data from these sources were both labor intensive and time consuming so flight test programs would extend over many years. The general test philosophy for a new aircraft design was to build a number of prototypes and fly as much as possible over a wide range of conditions in order to demonstrate freedom from problems and good overall behavior. From a flight test point of view, the 1950’s and 1960’s was a period of rapid technological advance and this, coupled with the continual drive for improved aircraft performance, led to many new problems being encountered. This inevitably resulted in incidents or accidents with a number of aircraft being lost and test pilots being killed or seriously injured.

When problems were encountered, further detailed flight testing had to be made in order to gain an understanding of the problems. The designers would attempt to generate fixes to solve each problem. Such fixes then had to be fully flight tested to determine their success or develop and flight clear a final fix that gave acceptable characteristics. Over this period, aircraft flight control systems progressed from comparatively simple systems with cables or rods connecting the pilots’ controls to the control surfaces, to more complex power assisted systems. As the combat aircraft flight envelope increased, control surface loads increased to the extent that hydraulic actuators were necessary to assist and eventually replace the pilot control forces. This in turn led to the requirement for artificial feel systems to give the pilot the correct cues in terms of control forces. As the quest for improved performance continued, the aerodynamic characteristics of new aircraft became more complex and it became progressively more difficult to produce satisfactory handling characteristics by aerodynamic means alone. Autostabilizers were introduced to improve the poor natural damping of the aircraft, but since these were simplex, they could only be of limited authority in order to survive in-flight autostabilizer failures. Autopilot functions were also included and utilized as either dedicated autopilot actuators or the autostabilizer subactuators in order to introduce the autopilot demands on to the control surfaces. The correct behavior of these systems had to be assessed in flight and so the flight test program had to include testing in both the normal failure free state and in each of the possible failure modes. In addition, system failure testing had to be performed in flight because loss of a system could result in potentially hazardous conditions. For example, loss of an autostabilizer function or loss of a hydraulic system, in certain parts of the flight envelope, could produce a significant transient aircraft response or degrade the aircraft handling qualities to the extent that control of the aircraft could be lost. Such in-flight failure testing required special test equipment and had to be approached and conducted with great care. For example, on the SEPECAT Jaguar, a special autostabilizer failure injection unit was fitted to inject hard-over or null failures in each of the axes of the 3-axis limited-authority autostabilizer system. Single hydraulic system failures were simulated in areas of the flight envelope where high actuator loads were experienced, in order to demonstrate satisfactory aircraft behavior. Such testing had to be performed in flight because of the relatively low level of confidence in the mathematical models of the aircraft and its systems at that time.

In the 1960’s and early 1970’s, technological advances took place that were to significantly impact the flight test process. These advances included the development of realistic and effective flight simulators; the development of airborne data acquisition and telemetry systems, and the development of powerful digital computers. Such computers could both process large amounts of test data and provide the ability to develop comprehensive models of aircraft aerodynamics, structures, and individual aircraft systems. These developments, together with the rapid advances in the field of electronics, led to the introduction of the concept of electrically signaled flight control systems, that is, fly-by-wire (FBW). Since control of the aircraft is a fundamental requirement (i.e., the FCS is a safety critical function); any such electrically signaled system must be fail safe. Thus early electrically signaled aircraft FCS, had a mechanical backup mode to ensure that control of the aircraft would not be lost under failure conditions. This again impacted the flight test task because flight testing had to be carried out in all possible failure modes to ensure that the aircraft could be recovered safely when failures occurred. Such electrically signaled flight control systems were multiplex analogue systems and the Panavia Tornado is typical of such a system. The Tornado command stability augmentation system (CSAS) is a triplex analogue system with a mechanical backup. However, the increased complexity of the flight control system meant that it was no longer feasible to inject worst case failures in flight since this would involve a failure injection device interfacing with all lanes of the multiplex system. Such a facility would have to be multiplexed in order to ensure that failures within the injection facility did not hazard the aircraft. Thus failure testing was done on a realistic flight controls rig as described in more detail later in this appendix.

With the rapid advances in microprocessor technology, the move towards digital FCS became feasible. In addition, studies into the concept of active control technology (ACT) and control configured vehicles had indicated that there were significant aerodynamic and structural benefits to be gained if these concepts could be incorporated into future combat aircraft. Such a step forward was considered so significant that a number of research programs were set in place both in the U.S. and in the United Kingdom (U.K.) in order to safely develop such systems. The first U.K. aircraft with a full authority digital FCS was the FBW Jaguar demonstrator aircraft. The aim of this national research program was the design, development, and flight demonstration of a safe, practical, full-time digital FCS for a combat aircraft. The prime objective was the identification of the design methodology and airworthiness criteria necessary for flight certification and throughout the program the FCS was to be treated in all aspects as though it were intended for production. Although it was not intended to demonstrate the aerodynamic benefits of ACT, the program included flight demonstration of the aircraft in a configuration that was aerodynamically unstable in the longitudinal (pitch) axis, and demonstration of a stall departure and spin prevention system. These aspects were considered crucial to the practical realization of ACT. It was also decided that the FBW Jaguar digital FCS would have no backup flight control system of any kind from the outset of the program. The reason for this was twofold. Firstly, a mechanical system could not control an unstable configuration. Secondly, an independent electrical backup, whether analogue or digital, would introduce so much additional complexity, both in the design of the system (hardware and software) and in the flight clearance processes, that it would be counter productive. From the flight test point of view any such backup system would almost certainly have to be tested in flight with all the associated hazards that this would involve. In the event, the decision to have no back up system was fully justified since other demonstrator programs (e.g., the U.S. (AFTI) F-16) had significant problems with their backup systems.

The FBW Jaguar program provided the UK with the vehicle to develop, in a cautious step by step approach, the ground and flight test clearance methodology necessary for a digital FCS equipped aircraft.

As a research program, the FBW Jaguar ground and flight trials were an outstanding success. The progressive approach provided a validated set of design, development, ground and flight test techniques, and procedures that could be used as the basis for all subsequent UK digital FCS programs. Having proved the principles of the digital FCS on the FBW Jaguar, the way was open to fully utilize the benefits of digital flight controls by producing an aircraft that was designed from the outset to take full advantage of the benefits of active control technology. That aircraft design was the experimental aircraft program (EAP) demonstrator. The objectives of this program were much wider than the FBW Jaguar program since it was to bring together a number of key new technologies required for a future combat aircraft. However, the digital flight control system was crucial to the success of the aerodynamic, structural, and avionic design and it fully utilized the experience gained from the FBW Jaguar. It also provided a major challenge to the flight test process and herald a significant change to the philosophy of flight trials. Previous UK flight trials programs had utilized telemetry to monitor each test flight, both from a trials safety point of view and to improve the efficiency of flight trials. However, most, if not all, of the test analysis was performed postflight. The advances in computing and modeling techniques, which had enabled the realization of digital flight controls, also made possible the concept of in-flight (real time) analysis of flight test data. The EAP demonstrator program provided the vehicle for the development of real-time analysis techniques for an aircraft with a digital FCS and these techniques have become the basis for flight testing the latest European combat aircraft, the Eurofighter.

2.0 PHILOSOPHY OF FLIGHT TESTING

As already indicated, the flight trials of an aircraft represents the only truly valid assessment of the performance and characteristics of the FCS in the total vehicle operating in its true element. However, the modern digitally controlled aircraft is so complex that the flight trials now represent only one part of the assessment of the aircraft and its systems. With the increasing ability to accurately model both the aircraft's aerodynamics and its individual systems, the flight test program is one part of an integrated development, flight clearance and flight certification program. The main emphases of the flight trials is now the validation of the models developed in the design and initial flight clearance of the aircraft as well as a demonstration of satisfactory characteristics throughout the flight envelope over the range of configurations and roles of the aircraft.

As a consequence, the flight test task begins in the design stage of the program and continues through simulation, rig test and aircraft ground test before proceeding to the actual flight trials phase.

3.0 GROUND TESTING

In order to understand the ground-test process, it is necessary to consider what actually makes up the FCS within the total aircraft.

The vehicle to be controlled by the FCS has structural and aerodynamic characteristics, which need to be defined prior to flight as accurately as possible as a prerequisite for the FCS design process. Theoretical methods and wind-tunnel tests of physical models are used to produce the structural and aerodynamic models required. These models need to be verified either on the ground or in flight. Clearly the aerodynamic model can only be verified in flight but the structural model can be partly verified on the ground and so ground tests are performed as a part of the clearance to flight process.

The FCS requires electrical and hydraulic power supplies with levels of integrity comparable to that of the FCS itself. Electrical equipment requires cooling and so the environmental control system is also important from an FCS point of view. If the FCS is the main source of air data for the aircraft, then the FCS interface to the cockpit displays also needs to be of high integrity to ensure that the pilot always has the flight reference displays that are required (e.g., airspeed, altitude, Mach number, angle of attack (AOA), normal acceleration, and attitudes).

The FCS itself is made up of a number of items of equipment. The heart of the system is the set of digital flight control computers (FCC), which are typically quadruplex (but may be triplex). These computers interface with a variety of input sensors, (pilot's controls, stick, pedal, throttle positions and a variety of switches), inertial sensors (gyros, and accelerometers), air-data sensors (pressures and flow angles to produce airspeed, altitude, Mach number, AOA, and sideslip), actuator position and status signals, and signals from other aircraft systems (e.g., weight-on-wheels and hydraulic pressures). The outputs from the FCCs are the actuator command and control signals and data required by other aircraft systems (i.e., air data signals for pilot displays and other subsystems). Each set of sensors and interfaces will have a level of redundancy appropriate to the requirement, so the primary FCS sensors will again be quadruplex. Within the flight control computers are a number of basic functions of direct interest to the test engineer. These are the control laws, the sensor processing functions, the actuator interfaces and the redundancy management, failure monitoring, and reporting systems. All these functions must be fully tested on the ground and test facilities are required to achieve this.

4.0 SIMULATOR AND RIG TESTING

The control laws are designed and developed using modeling and simulation. The design process requires both aerodynamic and FCS models. The FCS model contains the actuator, sensor and computer hardware/software characteristics so that the control laws can be designed and developed for the real system, (i.e., nonlinearities and computing delays are included). The aerodynamic models have a measure of uncertainty at this stage of the process and so each are represented by a nominal model together with a series of tolerances, which define the level of uncertainty of the particular aerodynamic coefficients. Having completed the initial design of the control laws using unmanned non real-time simulation, the full FCS and aerodynamic models are installed on the flight simulator for evaluation by pilots and engineers. Clearly, the simulation models must be validated against the design models to ensure correct implementation onto the simulator, which may have its own set of time delays.

The flight simulator contains a representative cockpit with outside world display to enable a detailed assessment of the control laws. This assessment is carried out over the full flight envelope for nominal and toleranced aerodynamic data so that any shortcomings in the control-law design can be identified and rectified. This assessment can often be an iterative process as problems are identified by pilots and referred back to the control law designers. The control laws are modified and reassessed using non real-time simulation before the updated laws are passed back to the flight simulator for pilot re-assessment. Once a satisfactory standard is obtained, the control laws are released for coding into the FCCs. The simulation task does not end at this point but moves into the next phase where it is used to perform a full assessment of the control laws over the full range of aircraft configurations planned for flight assessment in order to generate a flight clearance from a flight mechanics point of view.

In the UK, a number of manned simulation facilities have been used for the control-law design process. For example, at BAe Warton, a number of general-purpose simulators are available and the initial control-law design assessment can be performed on these where a generic cockpit is used. The detailed control-law assessment requires a more representative cockpit particularly in terms of pilot controls so this may be done on either a flight simulator specifically configured for the task or on the simulation facility contained in the FCS rig described in the next section. The advantage of the general purpose simulator is the very high quality of both the outside world displays and the computing capabilities contained in this facility.

The FCS equipment is tested on a ground-test rig. The rig itself can be as representative as considered necessary for the project involved. The most representative rig is the so called Iron Bird where the FCS and all the interfacing functions replicate the aircraft itself. The Iron Bird will have a configuration very close to the aircraft itself with the control surface actuators mounted in representative structures. All the cable runs and pipe runs will utilize aircraft standard equipment and will be run and mounted in a representative way. Aircraft standard electrical and hydraulic supplies will be utilized and the equipment racking will also be representative of the aircraft. An Iron Bird requires a considerable investment in equipment and facilities and in the U.K., recent practice has been to utilize a test rig that is less extensive in terms of representative aircraft structure, but is fully representative in terms of the FCS. This type of test rig is made up of a series of individual test benches, which can either be used independently or linked together to provide the complete system. It will also have all the interfaces (either real or simulated) that the FCS requires. The test rig will be made up of the following items:

a. FCC test bench,

b. Actuator test benches containing representative mounting structures and facilities to apply simulated aerodynamic loads,

c. Inertial sensors test bench,

d. Air-data sensors test bench,

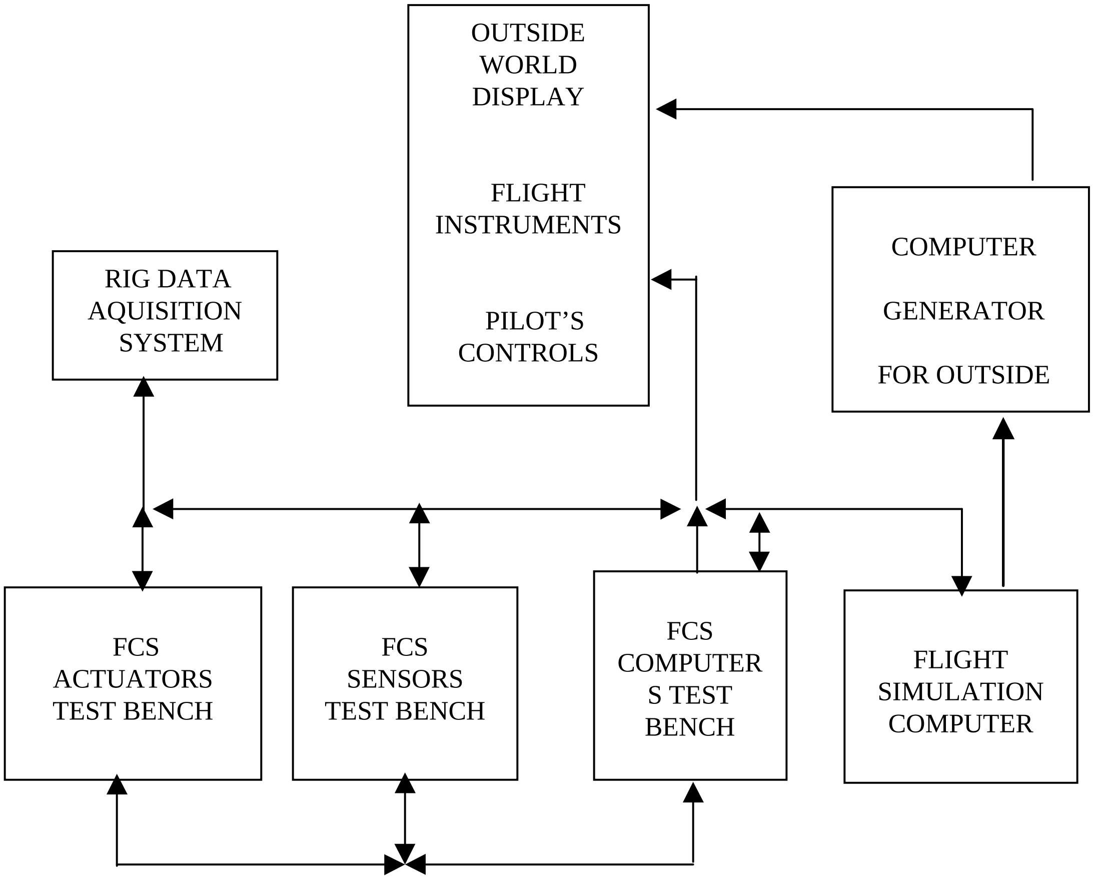
e. Other sensors test bench,

f. Simulation benches for sensors and actuators,

g. Cockpit with all FCS related equipment, representative flight instruments, and realistic outside world display,

h. Simulation computer capable of running the aerodynamic model, the FCS model, and any additional model functions (e.g., undercarriage, and atmospheric effects) as well as supporting the cockpit outside world display,
i. Real or simulated engine control system,
j. Real or simulated avionic and utilities control systems,
k. Hydraulic and electrical supplies capable of reproducing the aircraft systems in terms of pressures, flows and redundancy, and
l. Data acquisition and analysis system.

Figure B1 is a schematic of the FBW Jaguar ground-test rig and it can be seen that a high level of flexibility is provided by such a facility.


OUTSIDE WORLD DISPLAY
FLIGHT INSTRUMENTS
PILOT'S CONTROLS
COMPUTER GENERATOR FOR OUTSIDE
RIG DATA AQUISITION SYSTEM
FCS ACTUATORS TEST BENCH
FCS SENSORS TEST BENCH
FCS COMPUTER S TEST BENCH
FLIGHT SIMULATION COMPUTER

B1 Schematic of FBW Jaguar FCS Ground Test Rig

Simultaneous testing can be carried out on each of the test benches. Alternatively, different groups of benches can be linked with simultaneous testing being performed on each of these groups. Even for closed-loop testing (i.e., with a pilot in the loop) a number of different combinations are possible. These range from pure simulation (where the cockpit is linked to the simulation computer, which runs models of the full FCS and aerodynamics), through real FCCs with simulated actuators and sensors, to all real FCS equipment with the simulation computer simply closing the aerodynamic loop. This level of flexibility and simultaneous test capability is essential if the large amount of testing required to clear the FCS is to be accomplished in the minimum possible time period.

The principle tasks of the Rig test program can be summarized as follows:

a. To verify the control laws by pilot assessment before they are programmed into the FCCs,
b. To integrate the FCS hardware and software,

c. To validate the software actually implemented into the FCS,

d. To integrate the FCS with other aircraft systems including the flight test instrumentation system,

e. To gain a level of confidence in the overall system, and

f. To provide a facility for the pilots and engineers to prepare and train for flight trials.

4.1 Control Law Verification

As already indicated previously, the task of designing and verifying the control laws before implementing them in the FCCs is often shared between the general purpose simulators and the ground-test rig. What is of vital importance is that the models used on both facilities are both identical and thoroughly verified. The standard of each model must therefore be clearly defined and tightly controlled using a master data file that is only released to the test facilities when it has been thoroughly checked. Once installed on the test facility, check cases are run to ensure that the model is operating correctly. Any change to the models is first installed and checked out in a new issue of the master data file before being formally released to all the test facilities. Only in this way can it be ensured that the correct standard of model is used to verify and validate the FCS as fit for flight.

4.2 FCS Hardware and Software Integration and Testing

The ground rig provides the first opportunity to run the FCS equipment together as a full set of hardware. Usually the standard of software on first equipment delivery is low and simply enables the equipment to be powered up and run together. As each software function is implemented it is thoroughly checked out and debugged where appropriate to ensure correct implementation and operation. The built-in-test (BIT) functions, which will ultimately require a full set of FCS equipment, are also developed to ensure that they correctly identify all conceivable failure scenarios. The individual items of equipment are tested on their own benches. Thus performance testing (e.g., frequency and transient responses, impedance characteristics, and rate into load tests) is carried out on each of the actuators mounted in representative structures. These results are used both to confirm that the actuators meet their specification and to update/validate the actuator models. The inertial sensors are tested on rate tables and the pilot inceptors (e.g., control stick unit and sensors, rudder pedal assembly and sensors, and cockpit switches) are tested to ensure correct force/displacement and switching characteristics.

4.3 Software Validation Testing

This is the most demanding task placed on the rig since it is the final stage of an extensive software validation process. The FCS software must be of high integrity and free of unacceptable faults. It is therefore subjected to a series of tests of which the final phase is carried out on the rig. Before the formal rig test validation process can begin, the delivered software must shown to be free of faults. Thus, as each function is introduced into the software, it is fully tested and any shortcomings are corrected with software patches. Once a satisfactory standard is achieved, a formal configured standard of software is defined and released for implementing into the equipment. The formal software validation testing on the rig can then begin. If any of these formal tests fail, then a new standard of software must be produced and the whole process may have to be repeated.

The actual formal test process contains the following aspects:

a. Initial testing to ensure all previous system queries have been cleared.

b. Initial closed loop evaluation where the rig is operated closed loop using real FCCs programmed with the formal software. This evaluation also uses all other appropriate real FCS hardware. An experienced test pilot then flies a series of flight profiles to assess aircraft handling and system behavior over a wide range of flight conditions to identify any deficiencies and to give early warning of any possible software errors. This technique has been shown to be particularly effective in identifying potential errors in the new software release. Having established confidence in the system and its software, the full detailed test process can be initiated.

c. Full evaluation of the BIT functions to ensure no self-detected faults exist and a full sequence of failure tests to ensure that the BIT correctly detects and identifies each failure. These tests are of particular interest to the flight test engineers because the design of an FCS is such that any BIT failure will normally prevent the system from being engaged into its flight mode. Thus the engineers need to understand what can cause BIT failures and the differences between nuisance and hard failures.

d. Open-loop static dynamic and transient testing to ensure that the end-to-end characteristics of the system are correct. In this configuration, the aerodynamic loop is not closed (i.e., the system isopen loop) and each sensor to surface path is exercised over the full range of conditions. Static tests confirm correct gains, dynamic tests check gain and phase over the range of frequencies appropriate and the transient tests check the time variant aspects of the different paths and individual control-law elements. The results of each of these tests are compared with predictions from the FCS model. Since the number of tests can be of the order of 100000, they are automated as far as possible with the computer comparing each result with an acceptance band. Only when a test fails is operator intervention required.

e. Synchronization testing to ensure that the system obtains synchronization on start up and maintains or reestablishes synchronization correctly.

f. Timing testing to ensure that the time delays through the FCS meet the requirements and are correctly represented by the models.

g. Open-loop failure testing to ensure that the failure monitoring functions correctly detect and identify each different type of failure; that the voter and monitor thresholds and timings are correct and the correct system reconfiguration takes place. Again this testing is of particular interest to the flight test engineers because the pilot’s failure drills and procedures need to address all possible failure scenarios. The correct warnings must be shown to be generated for pilot displays and correct failure information generated for the failure recording and maintenance functions. Other aircraft system failures or specific FCS equipment hardware failures are also assessed where appropriate to ensure correct failure detection and system performance/reconfiguration.

h. Closed-loop dynamic testing with the simulation computer closing both the aerodynamic loop and the pilot loop to perform dynamic and transient tests the results of which are compared with the theoretical responses obtained from the model.

i. Closed-loop failure testing to ensure that when single or multiple failures are injected into the FCS, any transients produced are at an acceptable level and handling qualities remain fully acceptable following any FCS reconfigurations. For this testing, the rig is operated fully closed loop with test pilots or experienced test engineers flying the rig. The types of failures and the flight conditions at which the failures are injected are defined by a team of flight test and aerodynamics and systems engineers to ensure that all possible failure cases are included and the worst flight conditions and system configurations are assessed.

j. Closed-loop handling testing to ensure that the handling qualities produced by the control-laws software actually implemented in the FCCs is identical to that assessed during the simulation assessment and clearance process. This is done in all system modes and over the full range of mass and center-of-gravity (cg) positions to be flown. Also included are assessments of the FCS behavior following other aircraft system failures. For example, fuel system failures can result in large cg excursions and the behavior of the FCS in these conditions can be assessed. In fact, the rig can be use to assess aircraft and real actuator behavior under extreme conditions to ensure that there are no cliff edges present that could result in loss of the aircraft should they occur in flight.

k. Only when the formal software tests have been successfully completed can partial retests be considered. In the UK, a limited change clearance process was developed during the FBW Jaguar program. This process identified the minimum amount of software retesting that was required following a small change to a fully tested standard of software. The process has proved to be both safe and efficient in subsequent UK programs.

4.4 Inter-System Integration Testing

The FCS will interface with a number of other aircraft systems and such interfaces may be hardwired links or data-bus links.

System integration testing is performed to confirm correct operation of each of these interfaces under normal and failure conditions. In the case of the EAP facility, the FCS rig was capable of operating with simulated interfaces for the majority of the time, but a series of tests were performed with the FCS rig linked to the avionic rig and the utilities systems rigs for the final stage of the integration testing. Other aircraft programs have a dedicated integration rig. If changes are made to the software or hardware in either the FCS or in any of the interfacing systems, appropriate integration testing will have to be repeated.

A vital part of the flight test program is the aircraft flight test instrumentation system (FTI), which is used to record the data required for analyses. On modern aircraft, the majority of the FTI is extracted from the various data busses on the aircraft and, in particular, from the FCS. Thus the FTI FCS interface must be thoroughly tested on the rig to ensure correct functioning under normal and failure conditions.

4.5 Confidence Testing

Confidence testing is performed to generate operating experience with the FCS functioning as a complete system. It is performed with a full set of real equipment and with the rig operating in the full closed-loop mode. A series of representative 1 hour sorties are flown by pilots and engineers with each sortie including power-up BIT checks, takeoff, a formal handling test sequence, a period of free style handling, approach and landing, and system shutdown. This test sequence is flown as often as is considered necessary and is intended to exercise the system as fully as possible over as wide a range of conditions as possible. For example, prior to the first flight of a new aircraft a minimum of 50 sorties is considered necessary. Following subsequent software upgrades, a lower number will be performed.

4.6 Flight Trials Preparation

The rig can be used to provide the facility for the pilots and engineers to rehearse each test flight prior to execution. To do this, it can be used either in full simulation mode or with a full set of real hardware depending upon the state of the flight test program and the trials being performed. For example, the first flight of a new aircraft will be rehearsed with a full set of real equipment. Subsequent flights may be practiced on either the rig or on the flight simulator depending upon the actual flight trial involved. For example, the simulator outside world display will usually be of much higher quality than that on the FCS rig and so the flight simulator would be more appropriate for handling qualities testing.

The rig (and simulator) can also be used to provide a realistic training facility for pilots and engineers to practice drills and procedures for all possible failure scenarios. Even the most convoluted and potentially hazardous failures and emergencies can be practiced in complete safety!

5.0 AIRCRAFT GROUND TESTING

Before the aircraft is ready to commence the flight trials programa whole series of ground tests are required. These comprise FCS build tests, ground resonance and structural coupling tests, aircraft systems testing and electromagnetic compatibility testing

5.1 FCS Build Tests

The flight control system is fitted to the aircraft and fully functioned in the aircraft environment to ensure that the complete system design has been correctly implemented into the airframe. The build tests confirm that all the individual items of FCS equipment and all the FCS wiring are functioning correctly. The FCS build tests are integrated with the other system build tests to ensure that all the interfaces are correct. Thus the electrical, hydraulic, cooling, avionics and other systems must also be shown to be functioning correctly from a flight control system point of view. Within the FCS, all the actuators, sensors and pilot controls must be correctly rigged and harmonized and it must also be demonstrated that there are no sign reversals in any of the control paths. These build tests utilize an automated ground test facility known as the Automatic Test Equipment (ATE), which contains its own computer and interfaces directly with the FCS computer hardware via suitably protected interfaces.

5.2 Ground Resonance Tests

As already indicated, the design process involves the establishment of a series of models, which need to be validated during the ground and flight test program.

Ground resonance tests are performed to identify the various structural modes of the aircraft (e.g., wing, fuselage, fin, tailplane/canard, flap/elevon/elevator, and rudder) and provide the first set of data used to validate the theoretical structural model of the aircraft. For these tests, the aircraft is positioned in a suitable test facility (i.e., it may be suspended in a test frame or supported on airbags) so as to replicate the in-flight state. Suitable external excitation equipment is used on the different parts of the airframe and a large number of accelerometers are fitted to the aircraft to measure the structural responses and identify the actual structural modes.

The validated structural model is then combined with the aerodynamic and FCS models to predict the structural characteristics in flight.

5.3 Structural Coupling Tests

Structural coupling (or aeroservoelasticity as it is also known) is the phenomenon associated with the introduction of a high-gain flight control system into a flexible airframe. The FCS sensors (both motion and position) will detect not only rigid-body motions (used to control the aircraft), but also any structural mode oscillations (generated by the flexible structure) superimposed on these signals. If the attenuation and phasing of the structural signals are inadequate, then instabilities can occur. Such an instability is potentially catastrophic because it can result in either loss of control or severe structural/fatigue damage to the aircraft.

The flight control system is designed such that structural mode filtering is included in the control paths where the structural model of the aircraft indicates that potential instabilities can occur. A series of structural coupling ground tests are performed to identify the characteristics of relevant structural modes and to test the implemented structural notch filers. Suitable test equipment is used to drive the FCS actuators over the required range of frequencies and each FCS sensor is monitored to determine the characteristics of any structural response. The tests have to be done in a variety of aircraft configurations (i.e., different fuel states, a selection of external store configurations and various FCS states) in order to determine the full-filter requirements. The data are used to update the aircraft structural and FCS models. Structural notch filters are then designed using the complete aircraft structural/aerodynamic/FCS model.

Further on-aircraft tests are then performed with the notch filters implemented in the control laws in order to demonstrate satisfactory stability margins with the full-flight standard equipment. For all these tests, the aircraft has to be in as close to the flight ready condition as possible so that the test results are fully representative.

5.4 Electromagnetic Compatibility Testing

Electromagnetic interference (EMI) represents a serious problem for an electronic FCS since it provides a mechanism for potential common mode failures in a multiredundant FCS. Malfunctions caused by EMI can range between being insignificant in nature to causing catastrophic failures. The EMI can be both internally and externally sourced and the FCS design process must address these issues. The flight control computers, control surface actuators, sensors units (inertial and air data) as well as all pilot inceptors, switches, and all data bus inputs and wiring associated with the FCS must be designed to be resistant to all forms of electromagnetic interference. This will include radio frequency (RF), microwave, lightning and electromagnetic pulse (EMP) sourced interference.

Before the aircraft is flown for the first time, sufficient electromagnetic compatibility (EMC) testing is performed on the complete aircraft to ensure that the aircraft is safe to fly in the local electromagnetic environment. As the test program continues, EMC testing to clear the aircraft to the full electromagnetic threat levels is performed.

Initial on-aircraft testing will commence with the aircraft in an unpowered condition and either single loom or multiloom bulk current injection tests may be performed. An external antenna can also be used to radiate the aircraft at a number of different aircraft orientations and over a range of frequencies and transmitter characteristics (e.g., horizontally and vertically polarized). Measurements are taken at the FCS equipment to determine the level of current induced per unit of field strength. These results can then be compared with the results of equipment bench test results done at much higher test levels. Testing will then progress to the powered aircraft configuration and a range of tests will be performed. Typical tests are system interaction tests, onboard transmitter tests, and external transmitter tests.

System interaction tests are performed to ensure that all aircraft systems are mutually compatible with each other, and in particular with the FCS. Thus all modes of operation of each aircraft system must be selected and exercised during engine running tests to ensure freedom from cross system interactions.

Where appropriate, measurements may be made of transients produced on the aircraft electrical bus bars as manually or automatically switched functions are operated. All onboard transmitters are exercised across their frequency range at normal and, where possible, at enhanced power levels to ensure freedom from EMI.

Testing against external transmitters can also be performed in a number of ways. Traditionally, the aircraft under test has been exposed to each type of external transmitter likely to be encountered during its development and then ultimately its service life. Current test techniques utilize a test site with antennas capable of exposing the live aircraft to radiation over the appropriate range of frequencies.

Monitoring the behavior of the FCS during these tests can be done in variety of ways. One option is to use the instrumentation system, but this requires careful interpretation since the FTI system on an aircraft can itself suffer from EMI. (In fact, it may be more likely to suffer from EMI because it is not necessarily designed to the same high levels of EMC hardness as the actual aircraft systems.)

A better option is to use fiber-optic links from the FCS computers to a remote computer monitoring facility that can be used to monitor a large number of FCS signals against thresholds agreed in advance.

The generation of a clearance to fly in conditions of a high-lightning risk is also very important in an aircraft development flight program and is essential for a service aircraft. Such a clearance requires an FCS that can survive lightning strikes. When digital computers were first used in flight control systems, there was concern that their processors could be corrupted by the electrical pulses generated by lightning strikes. System hardware and cable-loom screening design processes have been developed to protect such equipment from lightning strike effects and these are particularly important on an aircraft with composite structures. Although equipment bench tests can be used to demonstrate equipment resistance to lightning strikes and EMP, it is now often considered necessary to perform whole aircraft lightning strike tests to validate the design and clearance process. Such a series of tests requires a dedicated test facility including a test frame tailored to the particular type of aircraft under test. Although such testing is usually carried out with an unpowered aircraft, there are occasions where some testing is performed with a live FCS. Whole aircraft lightning testing was carried out on both the FBW Jaguar and the EAP demonstrator.

5.5 Engine Running Tests

The final ground tests are a series of engine runs when the FCS and all other aircraft systems are functioned with the aircraft providing its own internal power. (Hangar checks utilize external rigs to provide electrical and hydraulic power to the aircraft systems.) These tests represent the first opportunity to function the complete aircraft in a fully representative flight condition. For the FCS, the full power-up and BIT functions are assessed together with the FCS interaction with the hydraulic, electrical, avionic, and engine systems.

6.0 FLIGHT TEST TOOLS AND TECHNIQUES

In order to assess the performance and behavior of an aircraft, an extensive instrumentation system is required. Until recently, the instrumentation system comprised a full set of independent sensors, which recorded the state of the aircraft and its systems. With the introduction of electronic FCSs and digital busses, most of the data required by the instrumentation can be recorded directly from the aircraft systems. Some additional independent sensors are still required such as accelerometers for flutter/vibration measurements, strain gauges and pressure transducers for load measurements, and other specific sensors such as temperature transducers. Telemetry is also required to make the flight test program both safer and more efficient. In particular, telemetry makes possible the in-flight analysis techniques described below.

In addition, a number of specific flight test facilities are required in order to carry out the flight test program. Such facilities will usually include a flight test noseboom with flow direction sensing vanes fitted and some form of flutter mode excitation equipment. The noseboom pressure sensors and vanes provide an independent measure of aircraft flight conditions (e.g., airspeed, altitude, AOA and sideslip) in order to facilitate calibration of the FCS air data sensors. The flutter mode excitation equipment is used to excite the various flutter modes of the aircraft in flight in order to demonstrate adequate levels of damping and hence validate the structural model of the aircraft. Other special flight test facilities are fitted for specific flight trials. For example, when high AOA trials are performed, there is a risk of departure from controlled flight and spin entry. Prior to the start of these trials, emergency recovery devices including a spin recovery parachute and alternative hydraulic and electrical power sources are fitted. These of course have to be tested on the ground and in the air before the start of the trials.

The current UK flight test philosophy of fly to validate the model requires a number of novel test facilities as well as new excitation and analysis techniques. These were developed over the recent flight test programs of the Tornado, FBW Jaguar and the EAP demonstrator as described in the following section.

7.0 FLIGHT TESTING

The flight trials assessment of an advanced digital FCS involves a wide range of test disciplines. These include, aerodynamic stability and control, aerodynamic loading, dynamic characteristics (flutter and structural interaction), air-data sensors, hydraulic and electrical systems as well as the total flight control system. Thus, from a FCS point of view, the objectives and sequence of the flight test program will be dependent upon the aircraft to be evaluated. The two flight test programs described illustrate the evolution of the flight test techniques now in use on the Eurofighter.

7.1 FBW Jaguar Demonstrator Flight Test Program

Full details of the very successful FBW Jaguar Demonstrator program can be found in References 1 to 4. The flight trials took place between 1981 and 1984 and telemetry was used throughout. Although the telemetry system was limited, it enabled efficient sortie management as well as providing safety monitoring and engineering backup for the test pilot. Detailed analysis was performed between flights to ensure satisfactory behavior of the FCS and to further validate the aerodynamic models. The FBW Jaguar commenced the flight-trials phase as an aircraft that was aerodynamically unchanged from a standard Jaguar and so the aerodynamic and structural models did not require validation. However, the aircraft was equipped with new primary control surface actuators; the control laws were completely new and the air-data sensors were also. Thus the initial objectives of the flight test program were not only to demonstrate the basic performance and integrity of the FCS, but to carry out an assessment of the aircraft handling qualities, calibrate the air-data system and validate the impact on the aircraft flutter characteristics of the new actuation system.

Once the air-data sensors were fully calibrated, the control laws were updated to use the validated air-data signals and the flight test program moved into the next phase. This involved a full handling qualities assessment including high AOA testing where the stall departure and spin prevention function of the control laws were fully evaluated. It also included the first flight trials assessment of the aircraft in a longitudinally unstable aerodynamic configuration (i.e., achieved using a large amount of lead ballast in the rear fuselage).

Up to this point in the program, the demonstrator aircraft had been a standard Jaguar with aerodynamic characteristics that were well established both from wind tunnel and flight data. However, the final phases of the program involved the fitting of large wing leading-edge extensions (strakes) in order to generate high levels of longitudinal instability. Since this resulted in significant changes to the aerodynamic characteristics, a new aerodynamic model was generated from theoretical and wind-tunnel data. This was used in the control-law design and flight clearance process, but required in-flight validation before maximum levels of instability could be flown. Since the demonstrator aircraft was highly augmented, conventional control inputs did not provide adequate excitation for extraction of aerodynamic characteristics (parameter identification). A new excitation technique was therefore assessed on the FBW flight simulator and validated in flight on the FBW demonstrator aircraft while it was still in the well defined standard Jaguar aerodynamic configuration. This technique required the pilot to apply a 3-2-1-1 control input, which would provide excitation over a range of frequencies and so enable successful aerodynamic parameter identification. The name 3-2-1-1 was derived from the fact that the duration of the pilot inputs was defined by the time signature 3t - 2t - t - t seconds as illustrated in Figure B2.

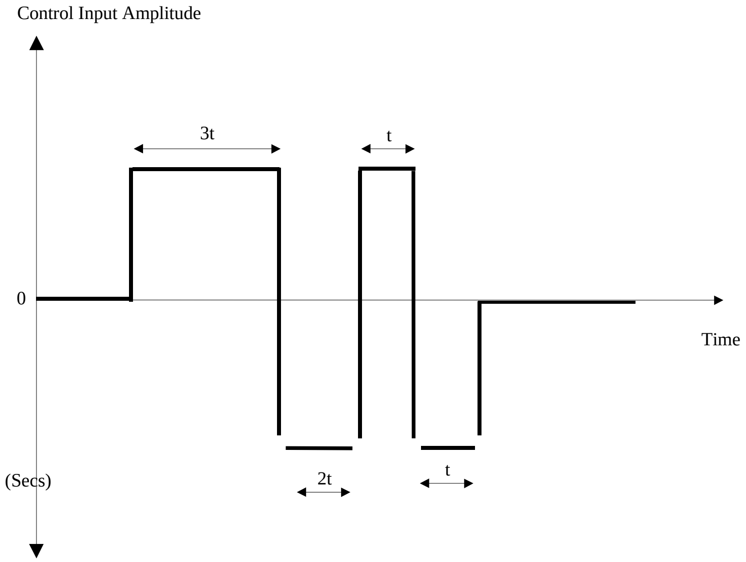


Figure B2 3-2-1-1 Control Input

When the large-wing leading-edge strakes were fitted, this technique was used to validate the new aerodynamic model of the aircraft. Initial flight trials were performed in a configuration with low levels of aerodynamic instability where the control laws were comparatively insensitive to tolerances in aerodynamic derivatives. Once the aerodynamic model had been shown to be within the tolerances used in the control-law design process, flight testing progressed rapidly to the maximum levels of instability.

The aircraft was successfully flight tested to high levels of longitudinal instability. The actual highest level of aerodynamic instability flown had a time to double amplitude of 250 msecs. This was completely transparent to the pilot since the FCS provided a very stable and maneuverable aircraft with excellent handling qualities. The step-by-step flight test program was fully vindicated and gave great confidence for subsequent digital FCS equipped aircraft development programs.

8.0 THE EAP DEMONSTRATOR FLIGHT TEST PROGRAM

The experimental aircraft program (EAP) evolved from a number of European studies into future combat aircraft requirements. These studies identified that a major requirement would be for a highly maneuverable aircraft for close and medium range air combat with a secondary, but effective, capability for air-to-surface battlefield support. This in turn would require a lightweight single-crew aircraft capable of carrying a wide variety of stores and twin-engined so as to provide a high level of survivability. To produce this within an acceptable cost would require extensive use of new technologies, many of which were either still at the conceptual stage, or in the early stage of development. In 1983, British Aerospace and the United Kingdom government signed a partnership agreement for a program to design and manufacture a demonstrator aircraft, which would integrate the new technologies. This EAP included an extensive flight test development phase to assess and prove the viability of the new technologies as a complete concept. A more detailed description of the program and its objectives can be found in References 5 and 6, but the following details are of particular relevance to this appendix.

8.1 The Demonstrator Aircraft

The aircraft, designed, built and flown during the program, was known as the EAP demonstrator. The airframe was a canard delta configuration with a structure containing widespread use of carbon-fiber composites and manufactured using an advanced co-bonding technique. The cranked delta wing with full-span trailing-edge flaperons and leading-edge droop, together with large authority moving canards (foreplanes) and a single fin and rudder resulted in an aerodynamic configuration, which was inherently very unstable (both longitudinally and directionally) and nonlinear. A full authority quadruplex digital FCS was designed to stabilize the airframe and to provide optimum Level 1 handling characteristics which would allow the pilot unrestricted use of controls, (carefree handling). This FCS was a further development of the FCS developed for the FBW Jaguar and as such had no backup electrical or mechanical system. More detailed descriptions of both the FCS and of the digital cockpit, avionic and aircraft systems can be found in References 5 and 7.

The initial objectives of the EAP demonstrator flight test program could be summarized as:

a. A progressive expansion of the flight envelope to establish confidence in the overall design of the aircraft and its systems.

b. A progressive assessment of the maneuvering capability of the aircraft provided by the combination of the advanced aerodynamic and structural configuration and the active FCS.

In order to achieve these objectives, a test to confirm satisfactory flight trials philosophy was to be used, the development of which is described in Reference 8. This philosophy can be described as an integrated flight clearance and flight assessment process whereby the aircraft is cleared to fly over the full flight envelope provided that the flight measured data can be shown to validate the toleranced aerodynamic models used in the clearance process. Such a philosophy requires analysis tools that can analyze flight data in near real time and provide the ability to compare the results with equivalent data generated from both the nominal and the toleranced aerodynamic models. In this way, if the flight data can be shown to lie within the predetermined model-generated boundaries of acceptability, the flight assessment program can continue with no delays for postflight analysis.

8.1.1 Analysis Techniques

The new analysis techniques set in place for the start of the demonstrator flight trials were designed to enable validation of the stability and control and loads models of the aircraft in quasi real time. These techniques are described in References 8 and 9, but can be summarized as follows.

8.1.1.1 Z Transform Analysis

This technique determined the frequency or real-root position for longitudinal and lateral/directional modes from small perturbation maneuvers such as 3-2-1-1 inputs or doublets. By comparing the in-flight results with data from the nominal and toleranced aerodynamic models, the aerodynamic model could be validated at each test condition within 2 minutes of the test input.

8.1.1.2 Comparison of Aircraft Response Data with Predictions

This technique compared the aircraft flight response data from large perturbation maneuvers with preflight prediction data for the nominal aerodynamic model at the test condition. The results were obtained immediately; the maneuver was performed by cross plotting specific response parameters in real time for comparison with the pre-prepared boundaries.

8.1.1.3 Aerodynamic Loads Analysis

Aircraft loads were computed from telemetered aircraft response data using the loads model hosted on the mainframe computer, which was linked to the telemetry facility computers via a fiber-optic link. Computed loads were compared with maximum allowable loads and results were available less than 30 seconds after completion of the test maneuver.

8.1.2 Parameter Identification.

Although this could not be accomplished in real time, the transmission of telemetered data to the mainframe computer made it possible for the process to commence as soon as the test maneuver was completed. Thus initial results could be available by the end of the test flight with full results a few hours later. However, this level of detailed analysis was not necessary if the techniques described previously showed that the aircraft was within tolerance.

8.1.3 Flight Trials

The flight trials of the EAP demonstrator aircraft commenced in August 1986 and the new analysis techniques enabled a rapid expansion of the flight envelope as described in Reference 5. In less than 3 weeks, 20 flights were performed validating the aerodynamic models to the extent that a full display sequence was cleared for the aircraft to fly at the Farnborough air show, which commenced 3 weeks after first flight.

The demonstrator flight trials continued until May 1991 (Reference 6) during which period significant development took place of both the FCS and the real-time analysis techniques. Since the aircraft and FCS configuration were very similar to that proposed for the Eurofighter, the EAP flight test program proved to be an effective risk reduction exercise for the Eurofighter development program as described in Reference 10.

9.0 FCS DEVELOPMENT DURING THE FLIGHT TEST PROGRAM

As already indicated, the EAP demonstrator FCS was a quadruplex digital system with no electrical or mechanical backup. The core of the system (e.g., rate and acceleration sensors, computing, actuator interface, pilot inceptors, and switches) was quadruplex, but the air-data system, which was integrated within the FCS was effectively triplex. Triplex Pitot-static data was provided by a noseprobe and two foreplane tip mounted probes with the noseprobe acting as the primary source. Triplex AOA and sideslip signals were derived from four airstream direction detector probes mounted around the lower surface of the nose. A double failure of the AOA/sideslip sensors would put the FCS into its reversionary mode. Loss of any two of the three Pitot-static probes would put the FCS into its fixed gains mode. The aircraft could be recovered from any part of the envelope following failure into the reversionary mode. However, the level of instability of the basic airframe was such that there were parts of the envelope where it could not be recovered in the event of a failure into the fixed gains mode. For a demonstrator aircraft, this was deemed to be an acceptable situation since the fixed gains mode had been originally conceived as a safe ejection platform only. This was because the air-data system was designed to be sufficiently robust as to make the likelihood of a reversion to fixed gains very remote. However, recovery procedures were developed on the ground-test rig with the pilots such that an optimum recovery profile was devised to ensure safe recovery following an air-data system failure. In the event, the design assumption was fully justified since there were no failures of the Pito-static system throughout the flight trials program.

The initial flight trials of the aircraft were performed with the FCS in its reversionary mode; the AOA and sideslip sensors were not used by the control laws but were fully active so that the wind-tunnel derived calibration could be validated in flight. In addition, the aircraft was ballasted to a forward cg position to reduce the level of instability. (Even in this configuration the level of longitudinal instability was such that the time to double amplitude was of the order of 250 msec, similar to the most unstable condition flown on the FBW Jaguar.) Once the air-data sensors had been calibrated over the initial flight envelope (Reference 10), the full system control laws were programmed into the FCS, the forward ballast moved, and the first phase of the carefree handling flight trials performed. Again, using the real-time analysis and model-validation techniques described previously, the initial carefree envelope was successfully cleared in 25 flights over a period of 4 weeks. Such a high risk flight trial meant that the aircraft was equipped with a spin-recovery parachute and appropriate emergency power supplies, as well as a spin recovery mode within the FCS. These facilities were never used in anger throughout the demonstrator program and this was due primarily to the success of the model validation techniques developed and used in the flight trials.

The last phase of the FCS development was the implementation of the final standard of control laws, which enhanced the subsonic carefree handling characteristics and introduced supersonic carefree handling. This was achieved by utilizing a blend of AOA and normal acceleration limiting together with the introduction of inertially derived AOA and sideslip signals as well as, attitude scheduling functions within the control laws. The development of the control laws is described in Reference 11 and the carefree handling flight trials in Reference 12. Pilot comment was extremely favorable (Reference 12) with quotes such as, “the aircraft and FCS withstanding the most savage abuse.” The real-time analysis tools again enabled rapid and successful assessment over the full flight envelope.

10.0 FLIGHT TEST AND ANALYSIS TECHNIQUE DEVELOPMENT

During the flight trials phase of the EAP demonstrator, a number of significant developments took place both in the provision of test facilities and in the use of real time model validation techniques. Of these, the provision of an in-flight structural mode excitation system within the FCS and the use of a real-time air-data system model validation analysis technique are of particular interest and are described in the following section. Other developments included the provision of a synthetic target tracking system (designed to demonstrate good handling characteristics and freedom from pilot-in-the-loop oscillations in high-gain tasks) and the development of an in-flight pressure plotting technique, to validate the aerodynamic loads model. More details of these can be found in References 10 and 13.

10.1 In-Flight Structural Mode Excitation

A facility to excite the aircraft structural modes via the aircraft control surface actuators were developed on the FCS ground-test rig and implemented into the Flight Control Computers FCCs (as described in Reference 14). This was achieved by generating quadruplex frequency sweep and impulse excitation signals within the computers and injecting them directly into the primary actuator control loops on to the foreplane and flaperon surfaces. Up to 63-pilot selectable test cases were programmed in to give a choice of surface, amplitude, symmetric or antisymmetric excitation and frequency sweep/impulse profile. The facility was tested over a period of 15 flights and shown to be very effective (Reference 14). In particular, it offered great potential to reduce overall test time when compared with conventional flutter mode excitation techniques since it enabled a large number of test points to be performed per test flight. (In fact, 83 test points were flown on one flight using this system.) In addition, it provided flight data that was subsequently used in the development of quasi real-time analysis techniques for use on the Eurofighter flutter flight test program (Reference 15).

The same FCS test facility was used to develop new test and analysis techniques that could measure both on-ground and in-flight structural coupling characteristics. These techniques would enable accurate dynamic structural models to be generated and subsequently verified in flight in order to determine optimum notch-filter requirements within the FCS. The aim was to demonstrate that a number of store configurations could be cleared into flight with a common notch filter design. This was successfully achieved as described in Reference 16 and the methodology and in-flight test philosophy developed were fed directly into the Eurofighter program.

10.2 Real Time Air Data Model Validation

The level of instability of the EAP demonstrator configuration resulted in high gains within the FCS control laws that were a function of flight condition. If airspeed errors were excessive, then FCS stability would be significantly reduced, particularly in transonic and supersonic flight. Although the noseprobe air-data correction coefficients were comparatively small and predictable, the correction coefficients for the foreplane tip mounted probes were both more complex and more difficult to predict, since they were a function of foreplane incidence as well as flight condition. During the supersonic envelope expansion phase of the flight trials, the actual difference between the noseprobe and foreplane-tip probe sourced air data was compared in real time with predicted differences generated in advance from the air-data model. Boundaries of acceptability were superimposed on the predictions that respected minimum FCS stability requirements. This proved to be very successful in that it identified errors in the foreplane tip correction coefficients, but confirmed in real time that the errors were acceptably small and so expansion could continue. Similar techniques were used later in the program when maneuvering to high AOA. The techniques developed, fed directly into the Eurofighter flight test program.

11.0 CONCLUSION

The ground and flight test development of modern combat aircraft equipped with complex digital flight control requires a test philosophy, which will be both safe and efficient in order to constrain the ever increasing costs of such programs. Within the UK, British Aerospace experience on the FBW Jaguar and EAP demonstrator programs has demonstrated that the concept of an integrated ground- the combination of real-time analysis and new test techniques and facilities have been shown to be effective in confirming the validity of the aircraft and systems models used in the design and flight clearance process. The techniques enable a more efficient and hence cost-effective development flight test program as is currently being demonstrated by the progress of the Eurofighter flight trials (References 17 through 22).

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14. Abstract

This document covers the basics of flying qualities flight testing for digital flight control systems. Most of the techniques and subjects discussed also apply to analog systems as well. The techniques discussed are by no means the only techniques available, nor are they necessarily applicable to every flight test program. Rather, they are a collection of best practices from organizations across NATO, which practice the subject matter. The author hopes that the contents of this text will provide a comprehensive overview of the subject appropriate for experienced engineers, as well as provide a learning source for those new to the subject matter.

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